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REPORT 81-14

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Wastewater treatment by a prototype
slow rate land treatment system

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Cover: Symbolic representation of slow rate land
treatment process

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Wastewater treatment by a prototype slow rate land treatment system

T.F. Jenkins and A.J. Palazzo

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Six slow rate land treatment prototypes, three containing a Windsor sandy loam and three containing Charlton silt loam, were studied from June 1974–May 1980. The systems were spray irrigated with either primary or secondary wastewater at application rates ranging from 2.5 cm/wk to 15 cm/wk. Application schedules were also varied. The performance of forage grasses was studied to determine the yield and nutrient uptake under the various application regimes.

The results indicate that, on a mass basis, an average of 91% of the nitrogen (N) applied could be attributed to either plant uptake or percolation of soluble N, mainly nitrate. Nitrate concentrations in the percolate were found to

20. Abstract (cont'd)

correlate with N loading rate. An N loading rate of 800 kg/ha resulted in a mean concentration of about 10 mg/L of NO_3^--N in the percolate. Plant uptake of N was linearly related to N loading rate at loading rates less than 800 kg/ha. In this range, plant uptake accounted for about 60% of the N applied.

Mean phosphorus (P) concentrations in the percolate were found to range from 0.03 to 0.07 mg/L P and depended only slightly on application rate. Removal of P averaged greater than 99% for all application regimes.

Water balance measurements indicate that evapotranspiration exceeded pan evaporation by a factor ranging from 0.86 to 1.17 over a 6-year period.

Treatment of biochemical oxygen demand (BOD_5), suspended solids, total organic carbon (TOC), and fecal coliform were excellent. Residual levels of BOD_5, suspended solids, and TOC in the percolate averaged 1.3, 1.2 and 1.8 mg/L, respectively. Fecal coliform bacteria in the percolate were reduced to detection limits independent of whether the wastewater was pretreated or disinfected before application.

A significant reduction in chloroform and other volatile trace organics was also found. Mean concentrations of chloroform were reduced from 9.6 $\mu g/L$ in the chlorinated primary wastewater to about 0.2 $\mu g/L$ in the test cell percolates.

No significant downward movement of heavy metals was found 5 years after suspension of heavy metal application.

Potassium (K) fertilization was found to be necessary to balance the low K/N ratio of the wastewater.

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SUMMARY

Municipal wastewater was applied to six large (152-cm-deep) outdoor lysimeters (test cells) in Hanover, New Hampshire, from June 1973 through May 1980. Three of the test cells were filled with a Windsor sandy loam; three were filled with a Charlton silt loam. Sprinklers applied primary or secondary wastewater at rates ranging from 5 to 15 cm/wk. The percolate was directed through a water meter and sampled with a composite sampler.

Water quality analyses were performed on the applied wastewater, on samples taken by suction lysimeters at various depths, and on the test cell percolates. These analyses included the forms of N (Kjeldahl, nitrate, ammonium), total and ortho-P, organic C, 5-day biochemical oxygen demand (BOD_5), total and volatile suspended solids, fecal coliforms and fecal streptococci, chloride, major cations (calcium, magnesium, sodium, potassium), pH, specific conductance, trace elements, and trace volatile organics (chloroform and toluene).

The test cells were seeded with a mixture of forage grasses in 1973. The plant material was harvested three times per year through May 1980. Plant yields were obtained for each harvest and samples were analyzed for N, P, K and occasionally trace elements. Mass removals of N, P and K were derived from this information and related to the quantity of these elements applied in the wastewater.

Water volume measurements for the applied wastewater, precipitation, and percolate indicate that the amount of "unaccounted for" water exceeded pan evaporation by a factor ranging from 0.86 to 1.17. This missing water was mainly attributed to evapotranspiration.

Water quality results indicated that N removal was the parameter that limited the rate of wastewater application. Nitrate was the predominant form of N found in the percolate, forming in the soil by nitrification of ammonium and moving through the soil with the downward percolating water. The concentration of nitrate in the test cell percolate correlated with the wastewater loading rate; an N loading rate of 800 kg/ha resulted in a mean concentration of about 10 mg/L.

Plant uptake was the major renovative mechanism for N. At annual N loading rates of 800 kg/ha or less, N uptake was linearly related to N loading rate and accounted for about 60% of the N applied. Mass balance information indicated that about 91% of the N applied to the test cells could be found in the sum of the plant uptake and the N (mainly nitrate) in the test cell percolates. In this system, denitrification accounts for less than 9% of the N applied.

Phosphorus treatment was excellent at all wastewater loading rates tested (up to 15 cm/wk). The resulting concentrations of P in the test cell percolates range from 0.03 to 0.07 mg/L, depending only slightly on wastewater application rate. The major mechanism for P removal was retention in the soil. Plant uptake was less significant except at very low P loading rates. Mean plant uptake of P ranged from 20 to 54 kg/ha/yr.

Removal of organic C, BOD$_5$, suspended solids, and fecal coliform bacteria was very effective and dependable. Mean concentrations of organic C, BOD$_5$, and suspended solids in the percolate ranged between 1 and 2 mg/L, independent of wastewater loading rate or whether primary or secondary wastewater was applied. Fecal coliform bacteria were removed from both disinfected and undisinfected wastewater to the limit of detection, one colony-forming unit per 100 mL.

We investigated the removal of ammonia and trace organic substances by volatilization during sprinkler application. This mechanism did not remove significant amounts of ammonia at the wastewater pH tested. Removal of volatile organics, however, was significant and lessened the concentration of these substances actually applied to the surface.

Following application, further removal of chloroform and toluene was observed. Mean percolate concentrations of chloroform were about 0.8 μg/L; mean percolate concentration of toluene was about 0.04 μg/L. The mechanism for this additional removal was not investigated.

Heavy metals were added to the raw wastewater and applied to the test cells for a year and a half at the beginning of the project. Analyses conducted in 1980 indicate that no significant downward movement of these metals has occurred 5 years after suspending heavy metal application.

Potassium deficiencies were found in soils and plant material after several years of wastewater application. This deficiency resulted from an imbalance in the K/N ratio in the wastewater. Application of K fertilizer corrected this problem and may have helped increase plant yields and N uptake as well.

WASTEWATER TREATMENT BY A PROTOTYPE SLOW RATE LAND TREATMENT SYSTEM

T.F. Jenkins and A.J. Palazzo

INTRODUCTION

General overview

The human population of the earth has grown from 1.1 billion in 1850 to over 4.2 billion in 1980. The production of waste materials has increased over this period to an even greater extent. Disposing of this enormous amount of waste material in an environmentally acceptable manner has become one of mankind's foremost problems. Domestic sewage accounts for a large part of the total waste produced. Methods to dispose of this material safely and economically are currently the subject of a large amount of research in the scientific and engineering communities.

Since human populations will inevitably produce sewage, man has only three options (Cillie 1978):

1. Concentrate the material in such a way that physical barriers can prevent it from interacting with the environment.
2. Disperse the material at concentrations too low to cause problems.
3. Return the material to the natural cycles from which it originated.

In the case of wastewater, the volume of material prohibits the use of option 1 except for components present at the trace level that can be efficiently segregated from the bulk material. Option 2 is attractive in locations with populations that produce sewage in quantities that are low in relation to natural flows of surface streams. Option 3 is the direction in which mankind has been forced to turn as the quantity of this waste material continues to increase.

The use of land application to dispose of sewage wastes was first documented in 1559 and its popularity increased through the middle of the 19th century (Wierzbicki 1949). During this period, sewage was extensively applied on land to dispose of it or to fertilize agricultural crops. While these land application systems were not designed to treat sewage, they apparently functioned well and no serious problems resulting from this practice were reported except where raw wastewater was used to irrigate fresh vegetables (Jewell, pers. comm.). Nuisance odors have been a problem for systems that were drastically overloaded. In the last half of the 19th century, land disposal was largely abandoned because of the rapid growth of cities and the resulting demand for nearby land (Cooke 1978).

From the late 19th century through the early 1960's in the United States sewage was usually collected and treated by a centralized sewage treatment plant and subsequently released into surface waters. These treatment plants were designed to reduce the amount of suspended matter and oxygen demanding substances prior to disposal in surface waters.

In the late 1960's, environmentalists began to question the practice of disposing of these partially treated wastes into surface streams. They were concerned with substances such as N, P, and trace elements that are not well treated by conventional treatment processes.

Two approaches were generally suggested to meet the more stringent treatment requirements: construction of new types of expensive advanced wastewater treatment plants specifically designed to treat N and P, and land application.

While land application had been widely used only a century earlier, little research had been conducted to assess its ability to meet today's treatment objectives

Nitrogen treatment

Nitrogen is present in sewage effluents in a wide range of concentration and in several chemical forms including organic N ammonium and nitrate

Nitrogen removal from wastewater is of concern for the following reasons

1 Ammonium and organic N can induce an oxygen demand in surface streams, causing unacceptably low dissolved oxygen levels
2 Mineral N often stimulates the growth of algal cells and can cause eutrophication of surface waters
3 Excessive nitrate concentration in drinking water is a public health concern, particularly for infants
4 Ammonia may be a toxic substance to many organisms in surface waters

The predominant forms of N in fresh domestic sewage are urea and proteinaceous material These organic forms of N quickly hydrolyze to ammonia in sewage collection systems Ammonia is the predominant form of N in raw wastewater when it arrives at sewage treatment plants (Metcalf and Eddy 1972) Primary treatment (the removal of large particulate matter by sedimentation) removes some organic N but has little effect on mineral N levels because of the high solubility of ammonium and the other forms of mineral N Secondary treatment processes vary significantly in design, but have a common purpose of further reducing the levels of oxygen demanding substances and suspended matter Most secondary treatment processes do not significantly affect the total N content but can transform the N into a more oxidized form such as nitrate

One potential benefit of land treatment is its ability to remove and utilize N (Reed et al 1972) For slow rate (irrigation) systems, the incorporation of N into plant material is undoubtedly the mechanism most responsible for its removal Other processes thought to remove N in these systems are immobilization within the soil biomass (soil storage), loss of ammonia to the atmosphere by volatilization, microbiological denitrification of nitrate, fixation of ammonium in clay minerals, adsorption of ammonium on organic materials, and chemodenitrification of nitrate (Lance 1975)

While this capacity to assimilate N is a major strength of land treatment, results at CRREL (Iskandar et al 1976) and elsewhere (Kardos and Sopper 1974, Hook and Burton 1979) have indicated that the leaching of nitrate may be the limiting factor in determining the wastewater loading rate in many cases This is because the applied N, mainly in the ammonium form, transforms to nitrate in the surface soil and translocates downward with percolating water

To maximize the N removal, research has focused on the various mechanisms that have been postulated to operate in these systems Research to assess the relative importance of these mechanisms in the field has generally met with significant problems Only the amount of N removed by vegetation has been well documented Denitrification, ammonia volatilization, and soil storage, while thought to be significant removal mechanisms by some, have not been measured carefully under field conditions Their importance is largely speculative at present

Since plant uptake is generally recognized as the most significant process for N removal in slow rate systems, success or failure will depend heavily on crop performance As a result, several studies have been conducted to measure crop uptake of N for various plant species Clapp et al (1978) recently reviewed most of these experiments Since plant species are living organisms they respond rather unpredictably to changes in application rate and schedule, specific soil characteristics, and climate

Palazzo and McKim (1978) studied plant uptake as a function of the amount of N applied They found that plant uptake of N increases with increasing application rates of N but does so at a decreasing rate Clapp et al (1978) also found this nonlinear relationship in crop uptake of N for various plant species

Although the amount of N applied appears to be a dominant factor in determining uptake, other variables have also been studied Clapp et al (1978) studied the ability of various plant species to remove N and found that perennial forage grasses could remove more N than corn With increasing application rates, N removal by corn reached a maximum of about 180 kg/ha Reed canarygrass, on the other hand, removed about 400 kg/ha of N under similar applications. Differences among various perennial grass species have also been reported by Larson (1974–1977), Sopper and Kardos (1974), Overman and Ku (1976), Deese et al (1977), Bole and Bell (1978), and Marten et al (1979), with reed canary-

grass, tall fescue, and orchardgrass generally removing the most N.

Palazzo and McKim (1978) studied plant uptake of N as a function of application schedule. No differences in crop removal of N were reported when 7.5 cm/wk of wastewater was applied in one continuous 24-hr application or in three 8-hr periods on consecutive days (2.5 cm/day). In addition, these investigators found no differences in uptake of N by plants when primary or secondary wastewater was applied.

Removal of N in land treatment systems by mechanisms other than plant uptake has been reported. In overland flow and rapid infiltration systems, microbial denitrification has been identified as a significant part of the overall N removal (Bouwer 1974, Thomas et al 1974, Aulenbach et al 1978). While reliable data on slow rate systems are lacking, denitrification has been estimated to remove from 15 to 25% of the N applied (EPA 1977). In order to sustain significant denitrification in the soil, however, at least three conditions must simultaneously occur: 1) the N must be present in the oxidized form, 2) oxygen levels must be low, and 3) sufficient organic C must be available as an energy source for denitrifying organisms (Lance 1975). Denitrification can also occur in reduced microzones within an otherwise aerated soil if the N and C requirements are fulfilled.

In typical slow rate land treatment systems, the soils are generally rather permeable and well aerated. The organic C content is generally low, particularly when secondary wastewaters are used, and the bulk of the organic C remains near the surface where the macroenvironment remains aerobic. These conditions do not favor denitrification.

Ammonia volatilization is another mechanism that may account for some N removal. Ammonia stripping has been used in sewage treatment plants for N removal and could potentially operate in land treatment. For irrigation systems, sprinkler application seems to have the highest potential for substantial ammonia removal by this mechanism. The pH of the wastewater is important in this regard since the amount of N present as free ammonia increases as the pH increases. The droplet size in sprinkler systems determines the surface-area-to-volume ratio and is important since ammonia loss occurs at this surface. The pressure at the nozzle and the diameter of the nozzle opening determine droplet size. The actual amount of N lost by volatiliza-

tion of ammonia in an operating system has yet to be determined, although it has been postulated to be a significant mechanism at the Werribee Sewage Farm in Melbourne, Australia (McPherson 1978).

The incorporation of N from wastewater into the soil biomass by immobilization can be an important factor. Seabrook (1975) reported that at the Werribee Farm the soil N has increased from an average 0.61% to 1.1% over the 48 years of wastewater application. This amounts to an average accumulation of 204 kg/ha/yr. A similar study at Bakersfield, California (EPA 1977), showed an average annual increase in soil N of 230 kg/ha over 36 years when a field irrigated with sewage was compared to a nonirrigated control area. On the other hand, observations at the Pennsylvania State University experimental system (Richenderfer and Sopper 1978) indicated a reduction of soil N in forest litter when wastewater was applied. This seems to imply that net mineralization is occurring in this system.

Soil N accumulation or depletion, however, is hard to document in short term studies because of the relatively large amount of native N present in the soil relative to that applied annually in wastewater, and because of the high spatial variation of native N in the soil. Only a few systems have been well documented. A change of only 0.01% in total soil N in the top 1.5 m of soil amounts to a change of over 1000 kg/ha in soil N.

Fixation of ammonium in clay minerals is a process unlikely to be of major significance for most slow rate systems. The soils used for this mode of land treatment generally have a high permeability and a low clay content. Chemodenitrification is also unlikely to be significant as a N treatment mechanism. Wastewater N is generally applied in the ammonium form and nitrification requires a pH above 5. Chemodenitrification, on the other hand, only occurs at a pH below 5 (Lance 1975) and can only take place after the ammonium has been nitrified. Adsorption of ammonium on organic matter could be important in a few slow rate land treatment systems if a large amount of soil organic matter was present in the soil profile.

Phosphorus treatment

Phosphorus is known to be a major stimulant for the growth of aquatic plants including algae (Schindler 1976). Since blue–green algae can fix N (the other major stimulant) from the atmosphere, P is thought to be the limiting nutrient

for aquatic growth in many freshwater systems. Algal blooms in surface water have in many instances caused eutrophication, resulting in undesirable conditions for both aquatic life and human recreation.

Phosphorus concentrations in domestic sewage generally range from 6 to 20 mg/L (Metcalf and Eddy 1972). Sedimentation removes a portion of this P, but most remains in the effluent. Advanced waste treatment processes for P that rely mainly on chemical precipitation using additions of alum, lime, or Fe(III) (Metcalf and Eddy 1972) are available but quite expensive. Their ability to meet phosphate discharge limits below 1.0 mg/L is questionable.

Knowledge of the potential of land application for P removal was largely based on agricultural research. Large numbers of agronomic studies have shown that most soils have an enormous assimilative capacity for P. Initially there was some concern whether these reactions, occurring at high concentrations near fertilizer granules (Reed et al. 1972), would occur at the lower P concentrations present with wastewater irrigation. Recent studies have shown that these reactions do occur in soils irrigated with wastewater (Enfield and Bledsoe 1975).

When wastewater is applied to the soil, the P that enters the system is either removed by plant uptake, lost by surface runoff, stored in the soil, or leached through the soil profile (Pratt et al. 1978). Except at very low loading rates, soil storage is thought to be the primary mechanism for P removal in land treatment. This removal is probably due to sorption and chemical precipitation as iron or aluminum phosphates at a soil pH below 6 and as calcium phosphates at higher pH (Reed et al. 1972). Since soils have a finite ability to retain P, the longevity of a land treatment site may be determined by its assimilative capacity for this element. At low loading rates, plant uptake of P may be an important removal mechanism, extending the life of a system.

Forage grasses have been shown to remove from 23 to 56 kg/ha of P annually when irrigated with secondary wastewater (Clapp et al. 1978). Palazzo and McKim (1978) found that at an annual P loading rate of 100 kg/ha, 30% could be accounted for in the crop. Similar results have been reported by Sopper and Kardos (1974). Although the range of P taken up by crops is narrow compared to N, differences have been found due to variations in P loading rate (Hook et al. 1974, Karlen et al. 1976, Overman and Ku 1976).

Several investigators have studied the ability of P to leach to the groundwater. Hook et al (1974), Dugan et al. (1975), and Deese et al (1977) among others found no evidence of P leaching to groundwater. On the other hand, Murrmann and Iskandar (1976) and Iskandar et al (1977b), studying a Warren very fine loam soil, and Karlen et al. (1976), studying a loam-textured soil, noted significant amounts of P leaching below the rooting zone. The reason for these differences is currently not well understood.

Several investigators have been attempting to develop a method to accurately predict the length of time a soil could be irrigated with wastewater (or the amount of P that could be added to a soil) before leaching of P would occur (Enfield 1977, Ryden et al., in prep.). Methods that use sorption isotherms have generally greatly underestimated the amount of P a soil can assimilate because the soils can mineralize (precipitate) P slowly from sorption sites and thus free these sites for additional sorption. Models based on solubility products of the various metal phosphates have also been attempted. At present, none of these techniques have been adequately evaluated to determine how well they predict the longevity of a treatment site for P removal (Enfield 1978).

Other considerations

Slow rate land treatment systems, except when they are underdrained, have no equivalent of an "end of the pipe" available to assess treatment efficiency. Researchers in the past have generally been forced to make judgments on treatment performance based on the analysis of soil solution samples collected at depth with suction lysimeters or from samples obtained from observation wells. It is now well recognized that suction lysimeters do not collect a sample representative of the natural drainage water (Quin 1978). The great horizontal variability of soils even over short distances is also well known (Keeney and Walsh 1978). Unless a large number of replicate samples are taken, the reliability of these data in assessing overall system performance is open to question. Since the expense of taking and analyzing large numbers of samples overwhelms most research budgets, smaller numbers of samples are generally the rule.

To obtain estimates of system performance on a mass basis, it is necessary to know not only the concentration of the constituent of interest, but also the volume element the sample represents.

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Since this volume was generally not measurable in previous studies, researchers had to estimate the volume each sample represented This is a major assumption, implicitly made in nearly all previous studies where investigators have attempted to determine the mass balance of wastewater constituents The treatment efficiency reported in these studies should therefore be viewed only as an estimate With the exception of plant uptake, quantitative assessment of the various renovative mechanisms cannot be inferred from their data

Experiment objectives

The objective of this study was to obtain reliable performance criteria for a slow rate land treatment system on a mass basis, thus determining its renovative capacity The experimental design of the study included application of both primary and secondary wastewater at several application rates and schedules to two different soil types Since these prototypes were totally enclosed, all of the drainage water could be directed through a water meter and sampled with a composite sampler This design resulted in an "end of the pipe" from which samples could be obtained The water leaving this system was the drainage water that would merge with natural groundwater below the site if the design was actually used in a full-scale system Accurate mass balances were possible with this system since all water applied to and draining from the system could be sampled and the actual volumes measured Some of the data obtained on the water quality and crops during this 6-year period have been reported elsewhere (Jenkins et al 1978, Jenkins et al 1981) as have the soil and climatic measurements (Iskandar et al 1979)

A second objective of this study was to obtain accurate numbers for plant yield and nutrient uptake to compare the relative importance of this renovative mechanism with other renovative mechanisms This comparison was possible because the large size of the plots would closely simulate field conditions

A third objective was to conduct the study over a time period long enough to ensure that the results obtained would be representative of "steady state" conditions rather than an initial performance period Long term changes in performance for substances such as P were also investigated

METHODS

Preapplication treatment

The sewage used for these experiments was taken from a Hanover, New Hampshire, municipal sewer main that serves a small housing development near CRREL The sewage was totally domestic from the beginning of the experiment, June 1973, through October 1977, when a new laboratory addition at CRREL was connected upstream of the withdrawal point The raw sewage was found to have higher concentrations of N than is typical for municipal waste (Metcalf and Eddy 1972) and was diluted with tap water for the first 5 years of this experiment Undiluted wastewater was used from 1978 through 1980 The raw waste was pumped to a primary clarifier with a detention time of 4 hr The primary wastewater then flowed into a splitter box that divided the flow approximately in half One half was disinfected with ozone and stored in subsurface concrete tanks for use in experiments that required primary wastewater The second portion flowed to an extended-aeration activated-sludge package plant The detention time in this plant was approximately 28 hr The outflow from this plant was also disinfected with ozone and passed to a second subsurface concrete storage tank where it was used for experiments requiring secondary wastewater

During the period June 1979 through May 1980, the wastewater was chlorinated before it was applied to cells 1 and 6 This was done by adding 2 l of aqueous sodium hypochlorite (bleach) to the primary holding tank (approximately 5300 L) The wastewater was mixed for 1 hr before the onset of application

In the first year and a half of the experiment, seven heavy metals, Cd, Ni, Pb, Zn, Cu, Hg and Cr, were injected into the raw wastewater before primary and secondary treatment The amount of each metal added was calculated to provide a concentration of 1 mg/L in the wastewater and to simulate an industrial component of otherwise totally domestic wastewater In February 1975 the addition of these metals was stopped A discussion of the fate of these trace elements has been presented elsewhere (Iskandar 1975)

It should be emphasized that the commercial ozonator used for disinfection broke down frequently during the experiment, resulting in periods when undisinfected wastewater was used for
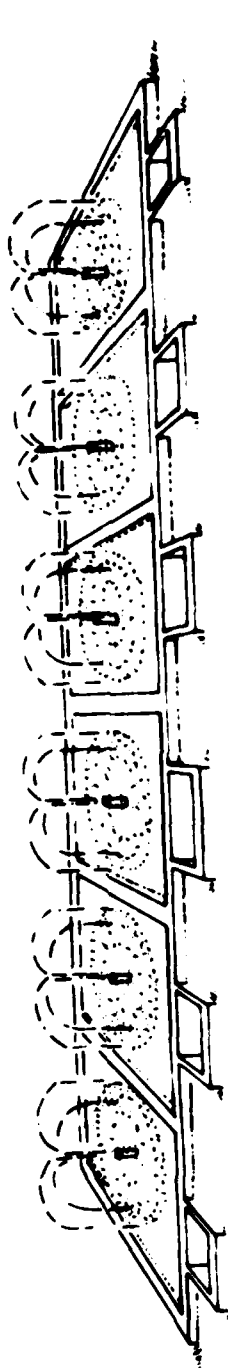
a. Overview of six test cells

8.5 m

8.5 m

Surface

			layer
A	15 cm	layer	
B	30 cm	layer	
C	107 cm		

7.6 cm

Slope 2.5%

Sampling Manhole

Horizon Samplers

A
B
C

Composite Sampler

Plastic Filter Cloth

Crushed Stone

Waste Pipe with Float Activated Pump

Water Meter

Sampling Tub

A
B

C Soil Horizon

20.3 cm
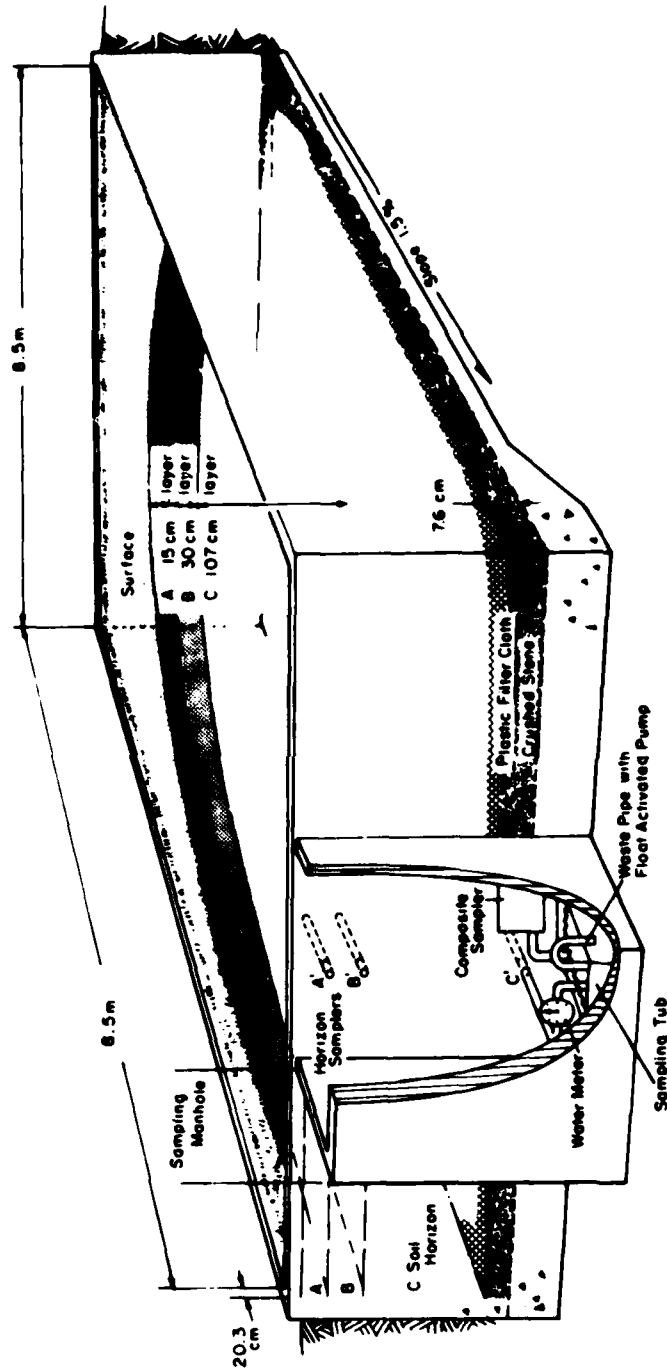
b. Design of each cell.

Figure 1. Diagram of CRREL test cells.

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land application Mean fecal coliform levels, reported later, are therefore not typical of wastewaters disinfected with ozone or chlorine For a more detailed description of the preapplication treatment used in these experiments, see Iskandar et al (1976)

Test cell design

The six test cells used for these experiments are large (8 5 × 8 5 m) outdoor lysimeters Iskandar et al (1976) present details of their construction They are constructed with reinforced concrete walls and bottom (Fig 1) Cells 1-3 were filled with Windsor sandy loam soil, cells 4-6 were filled with Charlton silt loam Both soils were obtained locally from the Hanover, New Hampshire, area, separated carefully into individual horizons, sieved to remove large stones, and carefully backfilled in the cells to simulate in situ conditions The total soil profile was 152 cm in depth The bases of the test cells were sloped toward sampling manholes that received all of the drainage water from each cell At the time of construction multiple suction cup lysimeters were placed in the soil at 15- and 45-cm depths to enable collection of soil solution samples

Wastewater application

Wastewater applications began in the early summer of 1973 and continued through May 1980 Table 1 presents the application rates and schedules used for each test cell over each yearly cycle Test cells 1 and 6 received secondary wastewater from June 1973 through August 1978 at an application rate of 5 cm/wk From August 1978 through May 1980 primary wastewater was applied, but the application rate remained the same The type of wastewater, the loading rate, and the loading schedule were variable for the other four test cells over the 6-year experiment (Table 1), depending on the research goals each year Cells 3 and 4 have received primary wastewater over the entire 6-year period, although the loading rate has varied on an annual basis

The period of the year when wastewater was applied to the cells is presented in Table 2 It should be noted that all six cells received wastewater throughout the winter of 1974-75 and test cell 6 received wastewater throughout the winter of 1975-76 as well Test cells 1 and 6 received wastewater until mid-January during the winter of 1979-80 also The remainder of the time applications were halted in late fall when the surface of the soils froze, application was resumed in the

Table 1. Wastewater loading rates (cm/wk) for CRREL test cells.

All applications were conducted at a 0 62-cm/hr rate during the spray season Flooding rates in the winters of 1974-75 and 1975-76 were somewhat higher

| Application period | Test cell | | | | | |
| | Windsor soil | | | Charlton soil | | |
	1	2	3	4	5	6
June 1973-May 1974	5-S* (1d)‡	10-S (2d)	5-P† (2d)	5-P (2d)	10-S (2d)	5-S (1d)
June 1974-May 1975	5-S (1d)	15-S (3d)	7 5-P (3d)	7 5-P (3d)	7 5-P (24h)**	5-S (1d)
June 1975-May 1976	5-S (1d)	15-S (3d)	7 5-P (3d)	7 5-P (3d)	7 5-P (24h)	5-S (1d)
June 1976-May 1977	5-S (1d)	2 5-12-P†† (1-4d)	2 5-11-P (1-4d)	2 5-11-P (1-4d)	2 5-11-P (1-4d)	5-S (1d)
June 1977-May 1978	5-S (1d)	7 5-P (1 5d)	7 5-P (1 5d)	7 5-P (1 5d)	7 5-P (1 5d)	5-S (1d)
June 1978-Aug 1978	5-S, P‡‡ (1d)	—	—	—	—	5-S, P‡‡ (1d)
Aug 1978-May 1980	5-P (1d)	—	—	—	—	5-P (1d)

* 5-S, 5 cm of secondary wastewater applied per week
† 5-P, 5 cm of primary wastewater applied per week
‡ d is the number of 8-hr application periods per week
** 24-hr application over one 24-hr period
†† Weekly applications varied between 2 5 and 12 cm/wk
‡‡ Changed from secondary to primary wastewater in August 1978

Table 2. Periods of test cell wastewater application.

Year	Test cell	Application seasons	
June 1973-May 1974	1	13 June 73-26 Nov 73	22 Apr 74-31 May 74
	2	9 June 73-26 Nov 73	17 Apr 74-31 May 74
	3	13 June 73-12 Dec 73	22 Apr 74-31 May 74
	4	13 June 73-12 Dec 73	22 Apr 74-31 May 74
	5	11 June 73-26 Nov 73	17 Apr 74-31 May 74
	6	13 June 73-26 Nov 73	22 Apr 74-31 May 74
June 1974-May 1975	1	2 June 74-31 May 75	
	2	2 June 74-31 May 75	
	3	2 June 74-31 May 75	
	4	2 June 74-31 May 75	
	5	2 June 74-31 May 75	
	6	2 June 74-31 May 75	
June 1975-May 1976	1	16 June 75-25 Jan 76	26 Apr 76-31 May 76
	2	16 June 75- 4 Jan 76	17 May 76-31 May 76
	3	16 June 75-30 Nov 75	
	4	16 June 75-30 Nov 75	
	5	16 June 75-30 Nov 75	
	6	16 June 75-31 May 76	
June 1976-May 1977	1	1 June 76-3 Dec 76	21 Apr 77-31 May 77
	2	8 July 76-3 Dec 76	21 Apr 77-31 May 77
	3	8 July 76-3 Dec 76	21 Apr 77-31 May 77
	4	8 July 76-3 Dec 76	21 Apr 77-31 May 77
	5	8 July 76-3 Dec 76	7 Mar 77-31 May 77
	6	1 June 76-3 Dec 76	21 Apr 77-31 May 77
June 1977-May 1978	1	14 June 77-6 Sept 77	10 Apr 78-24 May 78
	2	14 June 77-6 Sept 77	16 May 78-23 May 78
	3	14 June 77-6 Sept 77	16 May 78-22 May 78
	4	15 June 77-7 Sept 77	16 May 78-22 May 78
	5	15 June 77-7 Sept 77	16 May 78-22 May 78
	6	14 June 77-6 Sept 77	10 Apr 78-24 May 78
June 1978-May 1979	1	15 June 78-16 Nov 78	30 Apr 79-31 May 79
	6	15 June 78-16 Nov 78	30 Apr 79-31 May 79
June 1979-May 1980	1	1 June 79-29 Jan 80	18 Apr 80-30 May 80
	6	1 June 79-29 Jan 80	18 Apr 80-30 May 80

Figure 2. Photograph of test cells.

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spring. The application of wastewater to cells 2-5 ceased for the purposes of this experiment in June 1978 while application to cells 1 and 6 continued through May 1980. Water balance measurements for cells 2-5 were continued through 1980, however.

Wastewater was applied to the cells by sprinkler irrigation using a ¼-in. Fulljet nozzle mounted on a 26-in. riser (Fig. 2). The pressure was adjusted to cover a 7.6-m diameter spray circle within each test cell area (Fig. 1). The pressure was estimated to be about 30 psi. Spraying was discontinued when wind conditions caused the spray to land outside the cell area. Wastewater was flooded into the cells during the winter application periods in 1974-75, 1975-76 by removing the spray nozzles and allowing the wastewater to flow beneath the snow cover. During the winter application in 1979-80 the wastewater was sprayed upward against a flat plate that reflected it back to the surface in a manner similar to a device used for border strip irrigation (Fig. 5-11, EPA 1977). In either case the water was retained within the desired area by metal garden edging.

Soil characteristics

The soils used in the cells were Windsor sandy loam and Charlton silt loam. During construction, the A, B and C soil horizons were separated in the field, transported to CRREL, and placed in the cells. The soils were compacted to the original in situ bulk density to a 1.5-m depth. Iskandar et al. (1979) and Palazzo (1976) have presented in detail the initial characteristics of the soils before wastewater application and subsequent analyses over the course of the study.

Table 3 summarizes some of the most significant initial conditions. Table 4 presents the soil amendments applied to the cells and their application rates during the study. The soil amendments were applied to improve the balance of nutrients for plant growth and to increase soil pH.

Vegetation

The test cells were seeded with a mixture of reed canarygrass (*Phalaris arundinacea* L.), timothy (*Phloem pratense* L. var. 'Climax'), and smooth bromegrass (*Bromus inermis* Leyss. var. 'Lincoln') on 21 May 1973 at rates of 12.1, 6.6, and 5.5 kg/ha, respectively. The grass was allowed to establish itself for about a month before application of wastewater began in June 1973.

In September 1974, a botanical analysis of the vegetation within the area that received wastewater revealed that quackgrass (*Agropyron repens* L.) had become the dominant species in all six cells with lesser amounts of reed canarygrass, smooth bromegrass, Kentucky bluegrass (*Poa pratensis* L.), and perennial ryegrass (*Lolium perenne* L.). To obtain a more desirable vegetative cover on the cells and to smooth out the uneven soil surface that had developed because of soil settling, test cells 2-5 were reseeded in May 1976. Cells 1 and 6 were not disturbed. Quackgrass has remained the dominant species in cells 1 and 6 with increasing amounts of Kentucky bluegrass by the end of the study (June 1980).

During reseeding, the existing vegetation was killed with the herbicide glyphosate. Potassium chloride (300 kg/ha) was applied to the four cells. Dolomitic limestone was applied at the rate of

Table 3. Initial soil characteristics at the 0- to 15-cm depth.

Parameter	Windsor sandy loam (cells 1-3)	Charlton silt loam (cells 4-6)
pH	6.0	6.6
Soluble salts (mmho/cm)	0.20	0.32
Cation exchange capacity (meq/100 g)	7.0	13.5
Total N (%)	0.150	0.272
Total P (µg/g)	200.0	226.6
Total C (%)	1.71	2.34
Extractable P (µg/g)	26.2	23.1
Exchangeable Ca (µg/g)	552	725
Exchangeable Mg (µg/g)	26	45
Exchangeable K (µg/g)	49	35
Exchangeable Na (µg/g)	10	18
C/N ratio	11.4	8.6

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Table 4. Soil amendments (kg/ha) applied to test cells (May 1973 through May 1980).

Date of treatment	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Lime: Lime applied as dolomitic limestone (CaMgCO₃)						
1973	—	—	—	—	—	—
1974	—	—	—	—	—	—
October 1975	504	1497	1329	1497	1497	1665
28–29 May 1976 (during reseeding)	—	4492	3988	4492	4492	—
2 May 1977	2200	2200	2200	2200	2200	2200
1978	—	—	—	—	—	—
1979	—	—	—	—	—	—
1980	—	—	—	—	—	—
Total	2704	8189	7517	8189	8189	3865
Potassium: K applied as potassium chloride fertilizer (KCl)						
28–29 May 1976	—	300	300	300	300	—
2 May 1977	300	300	300	300	300	300
4 May 1978	137	—	—	—	—	137
4 May 1979	136	—	—	—	—	136
30 April 1980	140	—	—	—	—	140
Total	713	600	600	600	600	713
Phosphorus: P additions as superphosphate fertilizer (0-20-0)						
9 August 1976	—	41	41	81	81	—

7308 kg/ha to cells 2, 4 and 5 and at a rate of 6488 kg/ha to cell 3. The soil surface was then tilled and seeded with orchardgrass (*Dactylis glomerata* L. var. 'Pennlate') and reed canarygrass at rates of 33 and 22 kg/ha, respectively.

The lime and K fertilizer were applied to increase pH and exchangeable Ca, Mg and K in the soil. Past analyses of soils had shown reductions of these soil constituents (Palazzo 1977).

Problems were encountered in establishing an adequate grass cover after soil disturbance. Greenhouse experiments revealed that the plants produced greater yields when both K and P fertilizers were applied (Palazzo, unpublished results). As a result, P was applied to cells 2–5 on 9 August 1976 (Table 4). The grasses appeared to respond well to the P application and a good grass cover was obtained by the end of the season. The botanical composition of the grasses in cells 2–5 at the end of the study (June 1978) consisted primarily of orchardgrass with lesser amounts of reed canarygrass.

Climate

A detailed analysis of the climate at the Hanover, New Hampshire, site as it pertains to land treatment has been presented elsewhere (Bilello

and Bates 1978, Iskandar et al. 1979). Table 5 presents some of the pertinent information.

Analytical methods

Wastewater samples were obtained for analysis in two ways: 1) by collecting grab samples from the primary and secondary storage tanks and 2) by placing sampling cups on the surface of the test cells and catching a composite sample of the spray. Samples collected with method 2 for each application were used to obtain mass loadings for N, P and K. These samples were collected in narrow-mouthed brown bottles with a glass funnel in the neck to provide sufficient volume for the number of analyses required.

The percolate water from the test cells was collected several times per week over the 6-year period. In the first year (June 1973 through May 1974) only grab samples were collected. From June 1974 through May 1980, composite samplers were used to allow calculation of accurate mass balances on and off the cells. The soil solution was sampled with multiple suction cups at depths of 15 and 45 cm. During the first year, the soil solution was sampled weekly. The second year it was sampled biweekly. In the following years it was sampled irregularly. Winter freeze

Table 5. Climatic characteristics during study period, Hanover, New Hampshire (from Iskandar et al. 1979).

Latitude	43°43'N
Prevailing winds	northwest and south
Mean annual temperature	6.4°C
Total annual precipitation	95 cm/yr
Mean annual snowfall	185 cm/yr
Mean annual wind speed	6 km/hr
Evaporation	
1974-75*	66.65 cm
1975-76	69.49 cm
1976-77	54.62 cm
1977-78	52.99 cm
1978-79	51.29 cm
1979-80	50.37 cm
June 74-May 78 total	243.75 cm
June 74-May 80 total	345.41 cm

Monthly mean temperature and precipitation

	Temp (°C)	Precip (cm)
January	-8.9	6.9
February	-7.2	4.7
March	-0.1	6.1
April	6.0	6.3
May	13.2	8.5
June	17.8	11.0
July	20.0	7.4
August	19.4	8.2
September	13.6	9.1
October	7.1	10.5
November	1.8	7.8
December	-5.7	8.4
Total		94.9

*From June-May

and thaw tended to crack the porous ceramic cups used to collect the soil solution; as the experiment proceeded fewer and fewer were operable.

Figure 3 shows the various methods used to preserve or prepare samples prior to analysis. Five-day biochemical oxygen demand, suspended solids, fecal coliform bacteria, pH, and conductivity were analyzed the same day the sample was collected. Subsamples to be analyzed for organic C and major cations were acidified with a few drops of concentrated phosphoric acid to a pH of less than 2 the day they were collected. Another subsample was cooled to less than 4°C and kept cold until it could be analyzed for NO_3, NH_4^+, Kjeldahl N, total P, and ortho-P. Analyses of NO_3 and NH_4^+ were generally conducted within 2 days of sample collection and Kjeldahl N, total P, and ortho-P within 2 weeks.

Iskandar et al. (1976) detail the methods used to analyze the various parameters (also see Table 6). The accuracy of several of these methods has been periodically checked by analyses of certified samples of known concentrations supplied by the U.S. Environmental Protection Agency. Table 7 compares values obtained when these samples were analyzed as unknowns with the values provided by the EPA.

Grab samples taken from the primary storage tank and the test cell percolates were analyzed occasionally during 1979-80 for trace volatile organics. The samples collected off the test cell surface after spraying were also analyzed to assess the spraying process effect. Analyses were
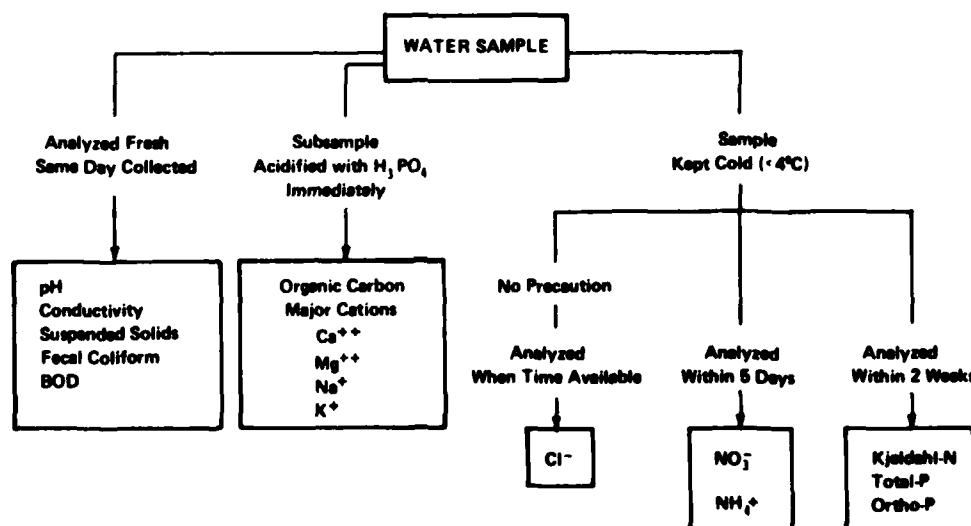
Figure 3. Summary of water sample handling procedure.

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Table 6. Summary of methods for water analysis.

Parameter	Date	Method	Range	Standard deviation	Instrument	Reference
NO_3	1973-74	Specific ion electrode	—	—		—
	1974-80	Automated cadmium reduction method	0-50 mg/L	0 3 (26)*	Technicon AAII	T I M No 246-73I†
	1974-80	Automated cadmium reduction method	0-1 mg/L	<0 1 (2)	Technicon AAII	T I M No 271-73W†
NH_4	1973-74	Specific ion electrode	—	—		—
	1974-77	Automated phenate	0-25/50 mg/L	0 17 (27)	Technicon AAII	T I M No 98-70W (1973)†
	1978-80	Salicylate/nitroprusside	0-25/50 mg/L	0 17 (27)	Technicon AAII	T I M No 329-74W/A
Kjeldahl N	1973-77	Technicon continuous flow digestion (V_2O_5)	0-25/50 mg/L	1 42 (6)	Technicon AAII	T I M No 146-71A (1972)†
	1978-79	Technicon block digestion	0-25/50 mg/L	0 70 (8)	Technicon AAII	Digestion T I M No 376-75W/B (March 1977) Analysis T I M No 329-74W /B (March 1977)
Total N	1979-80	Persulfate digestion	0-30 mg/L	0 40 (5)	Autoclave	Digestion Raveh and Avnimelech (1979)
					Technicon AAII	Analysis T I M No 329-74W /B (March 1977)†
Total P	1973-77	Technicon continuous flow digestion (V_2O_5)	0-10 mg/L	0 20 (7)	Technicon AAII	T I M No 116-71W (1972)†
	1978-79	Technicon block digestion (molybdenum blue analysis)	0-10 mg/L	0 13 (7)	Technicon AAII	Digestion T I M No 376-75W/B (1977)† Analysis T I M No 329-74W /B (March 1977)†
	1979-80	Persulfate digestion (molybdenum blue analysis)	0-10 m/L	0 22 (2)	Technicon AAII	Digestion Jeffries et al (1979) Analysis T I M No 329-74W /B (March 1977)†
Ortho-P	1975-79	Manual molybdenum blue	0-0 11 mg/L	0 003 (7)	Coleman Jr	HACH Chemical Co. Water & Wastewater Procedures**
	1979-80	Automated molybdenum blue	0-1 1 mg/L	0 01 (2)	Technicon AAII	T I M No 329-74W/B(March1977)†
Organic C	1973-78	Combustion, infrared	0-50 mg/L	2 0 (12)	Beckman 915	Beckman 915 Manual
	1978-80	Persulfate oxidation, infrared	0-4 mg/L 0-20 mg/L	0 2	O I C carbon analyzer	O I C Manual
BOD_5	1974-80	DO, Winkler method with azide modification	0-200 mg/L	1 5 (3)	Manual PAO titration	Standard Methods, 14th Ed, p 477††
Total suspended solids	1974-80	Filtration	0-200 mg/L	3 4 (6)	Analytical balance	Millipore procedure
Fecal coliform	1974-80	Membrane filter technique	100-10⁴/100 mL	275 (1)	—	Standard Methods, 14th Ed, p 937††
Fecal streptococci	1979-80	Membrane filter technique	—	—	—	Standard Methods, 14th Ed, p 944††
Chloride	1973-74	Specific ion electrode	—	—		—
	1974-80	Thiocyanate method	0-35 mg/L	1 4 (6)	Technicon AAII	T I M No 99-70W (1973)†
pH	1973-80	Glass (combination) electrode	5-9	0 07 (4)	Corning pH meter Orion pH meter	Standard Methods, 14th Ed, p 711††
Specific conductance	1973-77	Resistivity bridge	100-1000 µmhos/cm	36 (2)	Y S I conductivity bridge	Standard Methods, 14th Ed, p 460††
	1977-80	Resistivity bridge	100-1000 µmhos/cm	2 (3)	Resistivity bridge	
Ca^{++}	1973-80	Atomic absorption	—	0 14 (3)	Perkin Elmer 303 and 703	Methods for Chemical Analysis of Water and Wastes (1974), p 143‡
Mg^{++}	1973-80	Atomic absorption	—	0 03 (3)	Perkin Elmer 303 and 703	Methods for Chemical Analysis of Water and Wastes (1974), p 143‡
Na^+	1973-80	Atomic absorption	—	0 8 (3)	Perkin Elmer 303 and 703	Methods for Chemical Analysis of Water and Wastes (1974), p 143‡
K^+	1973-80	Atomic absorption	—	0 323 (3)	Perkin Elmer 303 and 703	Methods for Chemical Analysis of Water and Wastes (1974), p 143‡

* Numbers in parenthesis are the number of times a standard deviation was obtained
† Technicon Industrial Method, Technicon Instrument Corporation, Tarrytown, New York
** HACH Chemical Company, Ames, Iowa
†† American Public Health Association, American Water Works Association, Water Pollution Control Federation (1978).
‡ Environmental Protection Agency, EPA-625/74-003

Table 7. Results from analysis of EPA standard samples.

All values expressed in mg/L

Analysis	Known values EPA*		CRREL results 1976		Known values EPA†		CRREL results 1977		CRREL results 1978		CRREL results 1979		Known values EPA‡‡		CRREL results 1980	
	Conc 1	Conc 2	Conc 1‡	Conc 2‡	Conc 1	Conc 2	Conc 1‡	Conc 2‡	Conc 1‡	Conc 2‡	Conc 1	Conc 2	Conc 1	Conc 2	Conc 1	Conc 2
Nitrate (low)	0.20	2.0	0.20	2.0	0.11	1.1	0.11	1.1	**	1.1	**	1.0	0.11	11	0.11	11
Nitrate (high)	1.11	11.1	1.15	11.1	0.38	3.8	0.32	3.6	0.32	3.6	**	3.8	3.18	31.8	3.07	32.0
Ammonium (low)	0.44	4.4	0.38	4.3	0.23	2.3	0.0	1.2	0.25	2.2	0.15	2.4	0.19	19	0.17	19
Ammonium (high)	1.47	14.7	1.25	15.0	1.59	15.9	1.51	15.2	1.60	15.6	**	16.0	2.60	26.0	2.42	26.5
Kjeldahl N (low)	0.35	3.5	0.5	2.5	0.41	4.1	0.63	2.4	**	4.19	**	4.1	3.47	**	3.57	**
Kjeldahl N (high)	5.80	58.0	4.0	42.0	3.51	15.1	3.68	28.7	3.59	35.4	3.41	34.2	4.12	27.5	4.27	28.3
Total P (low)	0.142	1.42	0.25	1.5	0.20	2.0	0.22	2.1	**	2.17	**	2.5	0.47	0.93	0.43	0.91
Total P (high)	0.713	7.13	0.88	7.50	0.66	6.6	0.65	6.6	**	6.6	0.63	6.8	0.62	6.2	0.60	6.4
Organic C (low)	4.0	**	4.5	**	††	††	††	††	††	††	††	††	0.61	3.1	0.48	3.2
Organic C (high)	145	**	140	**	††	††	††	††	††	††	††	††	30	120	34	134
BOD5 (low)	3.3	**	3.3	**	**	**	††	††	††	††	††	††	2.9	**	1.8	**
BOD5 (high)	186	**	160	**	146	**	††	††	††	††	141	**	**	**	**	**
Ortho P (low)	††	††	††	††	0.052	**	0.058	**	0.053	**	0.058	**	0.03	0.78	0.03	0.75
Ortho P (high)	††	††	††	††	0.19	0.072	0.021	**	0.18	**	0.19	0.079	0.77	7.7	0.73	7.6
Conductivity					572	**	††	††	††	††	591	**	572	**	612	**
Chloride					176	220	††	††	††	††	170	216	110	220	111	220
pH					8.60	–	††	††	††	††	8.65	–	††	††	**	**

*First set of EPA samples apply to 1976 results

†Second set of EPA samples apply to 1977, 1978 and 1979 results

‡Concentration 1 is sample diluted according to EPA direction

Concentration 2 is a 10 fold higher concentrate of the same sample

**Sample not analyzed at this concentration since the other concentration provided adequate range

††Samples not available

‡‡Third set of EPA samples apply to 1980 results only

conducted immediately after sampling on a gas chromatograph/mass spectrometer (HP 5992) equipped with a purge and trap sampler (HP 7675a). Sixty milliliters of the sample were purged for 20 min and the Tenax collection tube subsequently heated to 200°C during the 5-min desorption period. The analysis was conducted on an 18- by ⅛-in. Porapak QS column, programmed from 90 to 200°C at 6°/min. A 5-min hold period at 90°C was employed during desorption from the purge-trap. Initial identification was obtained by matching mass spectra obtained to known spectra. Running the system in the selective ion monitoring mode gave quantitative determinations with a detection limit of about 10 ng/L.

Harvesting the forage grass three times per season gave plant yields and nutrient composition. The forage grass was cut to a height of 7.5 cm with a sickle bar mower. At each cutting plant biomass produced was calculated for each cell. The harvest dates were 3 June, 28 July, and 17 September in 1974; 12 June, 23 July, and 23 September in 1975; 8 June, 4 August, and 15 September in 1976; 1 June, 18 July, and 31 October

in 1977; 13 June, 19 July and 26 September 1978; 4 June, 25 July, and 13 September 1979; and 5 June 1980. Each harvest was collected and weighed to obtain the total fresh weight per cell. Random grab samples were dried at 70°C and dry weights per plot were calculated. The grab samples were commercially analyzed with standard procedures for N, P and K (Black 1965).

The quantity of N, P and K removed at each harvest was obtained by multiplying the dry weight of grass produced by the concentration of that element found by analysis.

Soils from all cells were sampled at the 0- to 15-, 15- to 30-, 30- to 45-, 45- to 75-, 75- to 105-, and 105- to 135-cm depths before the project started and in the spring of 1974 and 1975. In spring 1976, only soils from test cells 1–3 were sampled at the 0- to 15- and 15- to 30-cm depths.

Soils were air-dried and passed through a 2-mm sieve and then chemically analyzed. Soil properties analyzed were soil pH, with a glass electrode pH meter; total P, by the acid digestion procedure; extractable P, by the Bray P₁ technique (Bray 1948); total C, by the wet oxidation method (Black 1965), and exchangeable cat-

ions, by atomic absorption spectrometry (Jackson 1958).

RESULTS AND DISCUSSION

Wastewater composition

Wastewater was applied to the test cells from June 1973 through May 1980. Normally wastewater application began in mid-April and extended through the end of November (Table 2). During the winter of 1974-75, application was continued year-round. Wastewater was also applied through the winter to cell 6 in 1975-76 and through January to cells 1 and 6 in 1978-80. Both primary and secondary wastewater were applied through August 1978; after August 1978 only primary wastewater was applied. The type of wastewater and the application rate used each year is given in Table 1. The average composition of the primary and the secondary wastewater between June 1973 and May 1978 is given in Table 8. The concentration of total N in the two types of wastewater from 1973-78 was very similar, 28.0 mg/L in the primary and 26.9 mg/L in the secondary, demonstrating the lack of a significant mechanism for N removal in the secondary treatment plant (extended aeration). The

amount of nitrate was higher during warmer periods of the year in the secondary wastewater due to nitrification of ammonium in the aeration tank. This effect is shown in Figure 4, which presents the monthly averages of total N and of nitrate in the secondary wastewater. The total N ranged from 21 mg/L to 32 mg/L over this period, depending mainly on seasonal cycles and on the use of dilution water. The major N component throughout the year in both the primary and the secondary wastewater is ammonium, which averaged 24 mg/L in the primary wastewater and 18 mg/L in the secondary wastewater.

The average organic N content, as determined by the difference between the Kjeldahl N and ammonium, was low, about 3.4 mg/L in the primary wastewater and 1.7 mg/L in the secondary wastewater. The value of organic N obtained for secondary wastewater compares well with the range of 1 to 3 mg/L determined by McCarty and Haug (1971). The organic N content, as well as total N, increased substantially during 1978-1980 when fresh sewage from a laboratory addition was added to the sewer line just upstream of the intake point for this experiment (Table 9). The total N content during this period was about 38 mg/L.

On a seasonal basis, the nitrate composition

Table 8. Composition of applied wastewater during the period when both primary- and secondary-treated wastewater were used (June 1973 through May 1978).

All values expressed as mg/L except as indicated

Parameter	Primary Mean ± std. dev.	N*	Max.	Min.	Secondary Mean ± std. dev.	N*	Max.	Min.
Total N	28.0†				26.9†			
Kjeldahl N	27.4±8.4	232	71.5	2.5	21.0±11.1	138	50.5	1.5
Nitrate N	0.6±1.5	245	9.6	0.0	6.7±7.0	153	39.5	0.0
Ammonium N	24.0±8.7	233	77.0	0.0	18.3±9.5	139	40.0	0.0
Total P	7.6±6.7	230	95.0	1.0	7.3±4.7	136	48.0	0.8
BOD,	100±46	34	246	30	44±31	27	134	14
Organic C	55±21	159	136	2	39±25	99	109	4
Total suspended solids	85±177	69	1500	12	61±87	54	525	4
Volatile suspended solids	67±173	69	1460	0	39±73	54	521	2
Fecal coliform bacteria (no./100 mL)	$2.2\times10^5 \pm 2.7\times10^5$	37	9.2×10^5	3.9×10^2	$1.4\times10^4 \pm 4.8\times10^4$	25	2.4×10^5	2
pH (pH units)	7.3±0.3	178	9.0	6.6	7.2±0.5	117	8.3	6.0
Specific conductance (μs/cm)	419±102	205	660	120	425±107	122	720	100
Chloride	35.9±13.1	186	122	7.5	35.9±13.3	118	116	8.5
Calcium	9.3±9.1	12	28.7	2.7	11.8±11.1	17	47.6	5.0
Magnesium	3.0±1.3	12	5.6	1.3	2.9±1.3	17	6.3	2.0
Sodium	40.4±7.6	11	50.7	22.0	44.0±7.3	16	53.2	29.3
Potassium	8.2±5.0	76	21.8	0.0	10.0±5.8	46	26.2	0.3

* The number of analyses

† Obtained by adding Kjeldahl and nitrate values
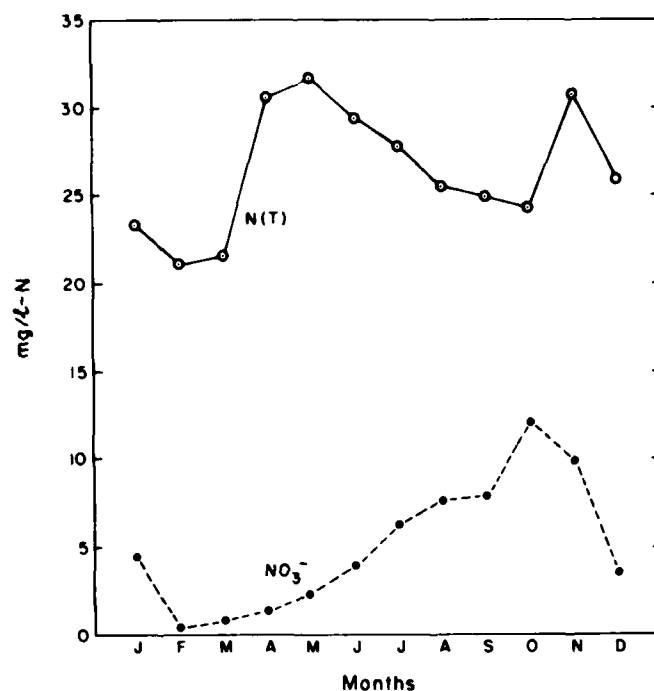
Figure 4. Average monthly total N and nitrate in secondary wastewater (June 1973 through May 1978).

Table 9. Composition of applied wastewater during the period when only primary wastewater was used (Aug 1978 through May 1980).

All values expressed as mg/L except as indicated

Parameter	Primary wastewater			
	Mean ± std. dev.	N	Max.	Min.
Total N	38 0 ± 16 2	46	117 7	19 0
Nitrate N	0 0 ± 0 2	65	0 9	0 0
Ammonium N	27 9 ± 12 7	65	83 1	6 4
Total P	6 9 ± 2 2	47	12 4	3 6
Ortho-P	4 2 ± 1 7	5	6 4	2 1
BOD,	91 ± 104	17	384	7
Organic C	73 ± 42	25	225	32
Total suspended solids	98 ± 105	16	290	8
Volatile suspended solids	68 ± 67	12	204	1
Fecal coliform bacteria (no /100mL)	$8 4 \times 10^5$	14	$4 2 \times 10^6$	0
Fecal streptococci bacteria (no /100 mL)	$2 4 \times 10^5$	3	$3 2 \times 10^5$	$4 6 \times 10^6$
pH (pH units)	7 6	49	8 6	7 0
Specific conductance (μmhos/cm)	547	44	895	315
Chloride	32 9 ± 15 1	20	83 3	19 9
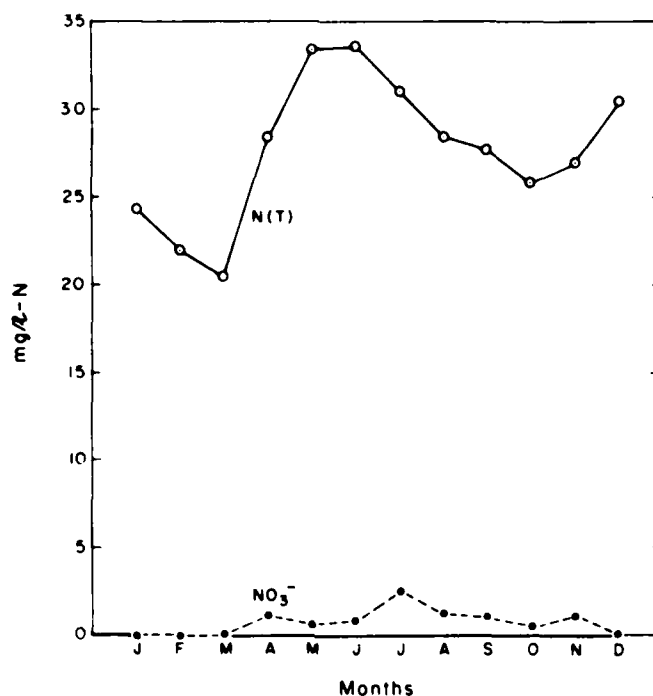
Figure 5 Average monthly total N and nitrate in primary waste-
water (June 1973 through May 1978)

of the secondary wastewater generally increased throughout the summer and finally peaked in October before declining sharply as water temperature dropped in early winter (Fig 4) The observed cycle is consistent with an increasing population of nitrifying organisms in the extended aeration plant during the warmer period of the year transforming a larger portion of the ammonium to nitrate

The nitrate content of the primary wastewater remains quite low throughout the year (Fig 5), indicating that there is no direct source of nitrate in the raw wastewater and that nitrification does not occur in the primary treatment process This wastewater is medium strength with respect to total N content (Metcalf and Eddy 1972)

Tables 8 and 9 give the mean P content of the wastewater Phosphorus concentrations averaged over 13 mg/L between June 1973 and May 1974, but have been in the 6- to 7-mg/L range since this time Secondary treatment resulted in only a fraction of a part per million reduction in P content This wastewater is medium to weak with respect to P content (Metcalf and Eddy 1972) Of the 7 mg/L total P found in the wastewater, all but about 1 to 2 mg/L is in the soluble ortho-P form

The mean suspended solids and BOD_5 of the primary wastewater between 1974 and 1978 were 85 and 100 mg/L, respectively These values characterize this waste as being weak relative to the ranges found in normal wastewater (Metcalf and Eddy 1972) The secondary treatment process used (Iskandar et al 1976) reduced the mean levels of total suspended solids and BOD_5 to 61 and 44 mg/L, respectively, somewhat higher than the 30 mg/L guidelines for secondary treatment The organic C level of the primary wastewater was only reduced from 55 to 39 mg/L by secondary treatment, a somewhat lower percent reduction than that found for BOD_5. The BOD_5 and organic C levels from 1978-80 were 91 and 73 mg/L, respectively.

The pH of the primary wastewater was generally found to be between 6 and 8 with a median value of 7.3. Secondary treatment did not substantially modify the range of values and the secondary wastewater had a median value of 7.2. The specific conductance of the wastewater ranged from 120 to 660 μs/cm for the primary and 100 to 720 μs/cm for the secondary, with mean values of 419 and 425, respectively The total salt content, as measured by the specific conductance, and the chloride ion content did

not significantly change in the secondary treatment process.

The concentration of fecal coliform bacteria in the primary wastewater was generally found in the 10^5 to 10^6 organisms/100 mL range, while that in the secondary was from 10^3 to 10^4 organisms/100 mL, a reduction of one to two orders of magnitude. The levels of fecal coliform organisms varied drastically due to the ozone disinfection unit's large amount of down time, which resulted in the lack of any disinfection during parts of this study. The levels of fecal streptococci were measured in the primary wastewater in 1979–80 and found in the low 10^5 range.

The mean concentrations of major cations, Na^+, Ca^{++}, Mg^{++} and K^+, in the secondary wastewater were 44.0, 11.8, 2.9 and 10.0 mg/L. This corresponds to a sodium adsorption ratio (SAR) of about 3. This is much lower than the value of 15, which is usually considered to be the critical level for reducing soil permeability (Reed et al. 1972).

The trace volatile organic composition of the wastewater was studied during 1979–80. The most significant components were generally chloroform and toluene. Their concentrations in chlorinated wastewater varied significantly from day to day, ranging from 9 to 13 µg/L for chloroform and 4 to 93 µg/L for toluene. With unchlorinated wastewater, the chloroform and toluene concentrations were somewhat lower indicating they were both produced in the chlorination process. Several other components, including methylene chloride, bromodichloromethane and tetrachloroethylene, were occasionally detected at lower concentrations.

From November 1974 through May 1980, low concentrations of a series of volatile organic substances were added to the wastewater applied to the cells.

Sprinkler application

Ammonia stripping is a technique which has been used successfully with high pH wastewater to remove N in conjunction with conventional treatment. It has also been mentioned as a possible mechanism of removal when wastewater is applied to the land by sprinkler irrigation (Lance 1975), although little information is available to assess its significance.

We took samples of the wastewater applied to the CRREL test cells from the holding tanks before application and from the surface of the test cells after sprinkler application. Table 10 compares the concentration of ammonium in the samples from these two. Nitrate values are included since some nitrification can occur while the sample is being collected on the cell surface; this conversion is not related to ammonia volatilization. By comparing the sum of ammonium N and nitrate N before and after sprinkler application, the extent of ammonia loss can be assessed. The assessment, however, is relative to water loss since spraying undoubtedly causes some volume reduction. The mean pH of the primary wastewater was 7.3, that of the secondary wastewater was 7.2.

For primary wastewater, the mean value of the sum of ammonium N and nitrate N decreased slightly from 25.5 mg/L before spraying to 24.2 mg/L after collection on the surface of the cell (Table 10). For secondary wastewater, the mean value decreased from 23.8 mg/L to 22.9 mg/L. While these values are consistent, they were not found to be statistically different using the Students t-test. Thus no statistically significant loss of ammonia in excess of the water loss was found during sprinkler application of wastewaters with pH values near neutrality.

We also analyzed the wastewater before and after spraying for trace volatile organics on a

Table 10. Ammonium and nitrate in applied wastewater (mg/L) before and after sprinkler application (20 November 1974–19 March 1978).

Ammonium and nitrate	Primary wastewater		Secondary wastewater	
	Before spraying	After spraying	Before spraying	After spraying
NH_4^+	25 3 ± 8 2* (158)†	23 9 ± 7 4 (168)	19 7 ± 8 9 (154)	16 6 ± 9 1 (102)
NO_3	0 2 ± 1 2 (160)	0 3 ± 1 0 (170)	4 3 ± 6 4 (158)	6 3 ± 6 7 (108)
$NH_4^+ + NO_3$	25 5 ± 8 3	24 2 ± 7 5	24 0 ± 11 0	22 9 ± 11 3

* Standard deviation
† Numbers in parentheses are the number of individual analyses over this period

Table 11. Reduction of volatile organics concentrations during sprinkler application.

Substance	Before spraying	After spraying	Percent removal
	Mean concentrations ($\mu g/L$)		
Chloroform (6)*	41 8	14 0	66.5
Toluene (4)	57 3	24 4	57 4
Methylene chloride (4)	7 61	2 32	69 5
1,1 dichloroethane (5)	30 2	9.88	67.3
Bromodichloromethane (1)	11 1	3.98	64.1
Tetrachloroethylene (4)	61 9	22.7	63.3
Acetone (3)	2 56†	1 39†	45 6
Ethyl acetate (3)	1.97†	0.85†	56 8

*Numbers in parentheses indicate number of times this substance was studied
†The numbers are relative abundances, not $\mu g/L$

number of days from August 1979 through May 1980. Initially this was done with chlorinated wastewater and later with wastewater to which a number of volatile organics had been added. The results are presented in Table 11.

In all cases the concentrations of volatile substances were significantly reduced, ranging from 45% for acetone to 69% for methylene chloride (Table 11); chloroform removal averaged 66%. Sprinkler application appears to be an important mechanism for reducing trace volatile organics during the spraying process.

Soil water movement

The treatment efficiency of a slow rate system is more difficult to assess over the short term than that of a conventional treatment plant because the water arriving at any given point in the soil profile probably was applied to the system at least several days previously. The travel or re-

tention time in the soil will generally not be constant but will vary with the application rate, the amount of precipitation and evapotranspiration, and the initial soil moisture.

To estimate retention time in the test cells, we determined the chloride concentration of samples taken from the 45-cm suction lysimeters and from the percolate at the bottom of the 152-cm profile after potassium chloride fertilizer was applied in April 1977. Smith (1972) and Nakano and Iskandar (1978) have used chloride to trace water movement in soils because it does not significantly interact with soil materials. Figure 6 shows the results for test cells 1 and 6. These retention times are for an average application rate of 4.8 cm/wk for cell 1 and 3.8 cm/wk for cell 6 over this period. In both cases, wastewater was applied once per week. The retention time in the top 45 cm for cell 1 was about 35 days, for cell 6 it was about 55 days (Table 12). The retention time in the entire 152-cm profile was 67 days for cell 1 and 81 days for cell 6. The retention time for cell 1 (Windsor soil) agrees well with results reported by Nakano and Iskandar (1978) from a lysimeter study using the same soil and a similar application rate. The retention times for the other cells and the average application rate used over this period are given in Table 12.

It should be emphasized that these retention time values depend on the time of year and would be somewhat different (generally shorter) during other periods. Nevertheless, the information does point out that percolate concentrations of substances such as nitrate, which move through the soil in a manner similar to chloride, stem from wastewater applied considerably before the percolate appears at the bottom of the cell.

Table 12. Average retention time of water in test cell soil profile (April through September 1977).

Test cell	Avg. application rate over test period (April–July) (cm/wk)	Retention time in top 45 cm (days)	Retention time in 152-cm profile (days)
1	4 8	35	67
2	3 0	55	77
3	3 0	62	77
4	3 5	64	81
5	3 1	64	81
6	3 8	55	81
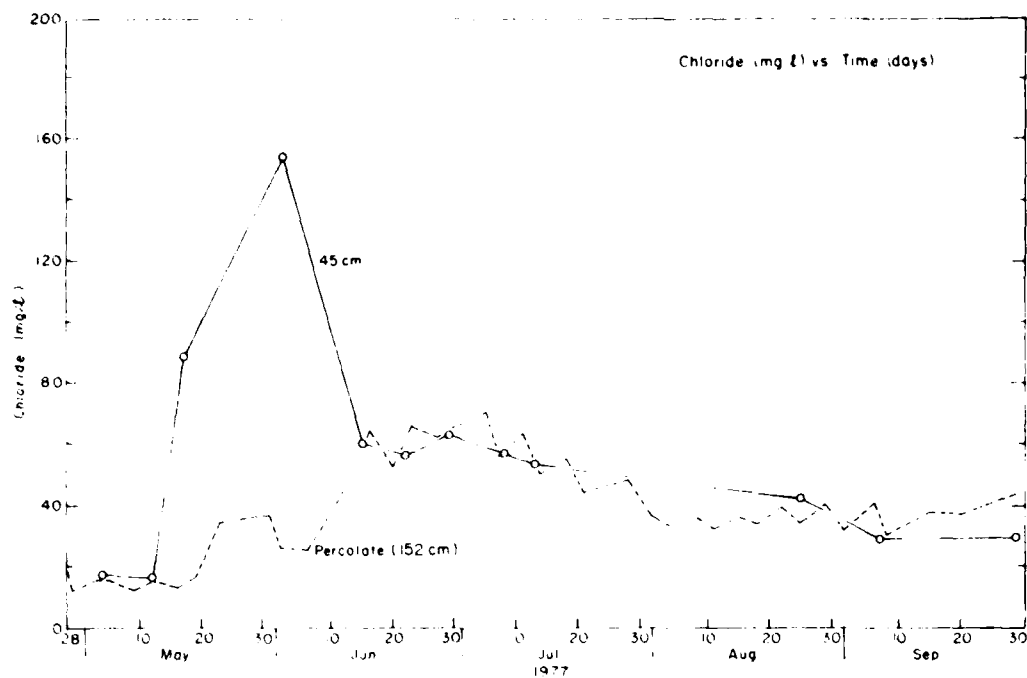
a. Test cell 1.
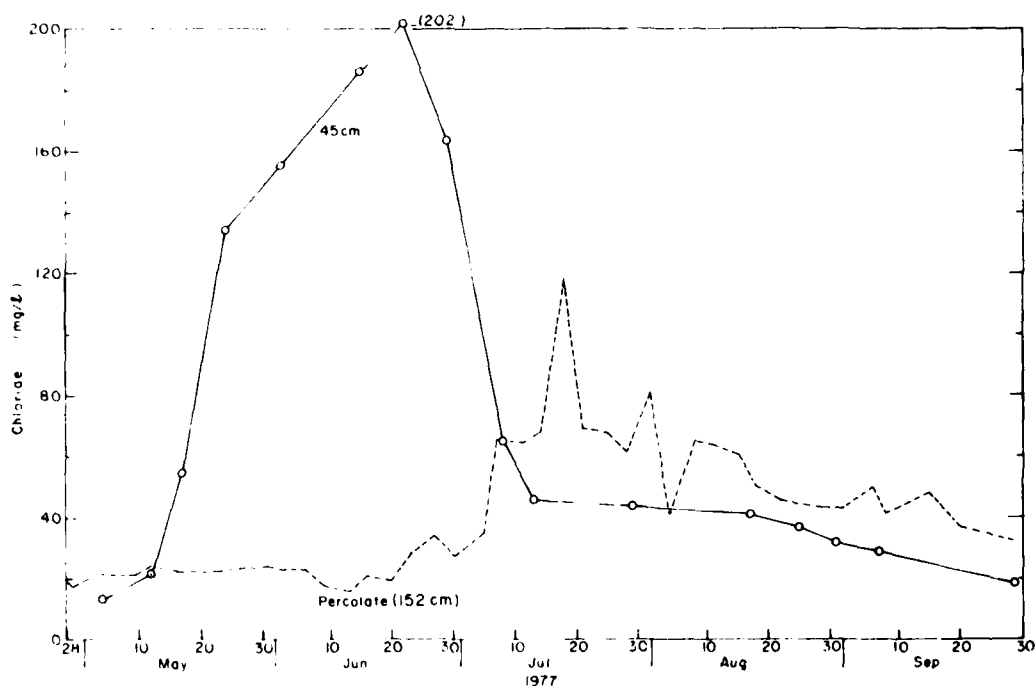
b. Test cell 6.

Figure 6. Chloride ion concentrations in soil solution at 45- and 152-cm depths after KCl fertilization.

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Table 13. Test cell water balance (L), June 1974 through May 1980.

Test cell	Wastewater applied	Precipitation*	Total applied	Percolate	Difference†	Pan evaporation**	E_t/E_p (× 100) (%)
1	435,723	392,627	828,350	539,657	288,693	251,538	115
2††	711,807	392,627	1,104,434	831,398	273,036	251,583	109
3††	458,463	392,627	851,090	633,591	217,499	251,583	86
4††	440,346	392,627	832,973	597,972	235,001	251,583	93
5††	446,395	392,627	839,022	573,522	295,500	251,583	117
6	453,504	392,627	846,131	570,486	275,645	251,583	110

* Calculated on a cell surface area basis of 76 790 m², which included ½ area of concrete side walls
† This value is the total applied minus the measured percolate
** Calculated on a 72 836-m² cell surface area
†† June 74 through May 78

Water balance and evapotranspiration

The design of the six test cells allows the water applied and the water leaving the test cell to be precisely measured. Since June 1974, all of the water applied to the cells and all of the water percolating to the bottom of the 152-cm profile has been metered. The amount of precipitation and pan evaporation has also been monitored carefully over this period. A yearly water balance for each cell is presented in Appendix Tables A1 through A6.

A summary of the 6-year water balance totals is presented in Table 13. The *Difference* column represents the total water applied including precipitation minus the total water percolating from the base of the cells. Soil water content over the 5-year period is assumed to be identical at the beginning and end of the tabulation period. This assumption is probably valid because wastewater had been applied for a year before the start of the tabulation period. In addition, the start and end of the period were at the same date (1 June) so that seasonal variations in soil moisture would be minimized.

As can be seen in Table 13, the difference in the amount of water applied versus the amount of water percolating to the bottom of the cells exceeded the measured pan evaporation in all cases.

The difference between the amount of water applied to the cells and the amount of water percolating to the bottom of the cells is a result of plant evapotranspiration, sublimation from the snow pack during the winter, aerosolization and evaporation during the spraying process, and spray blown off the cells on windy days. This last contribution should be minimal since applications were halted when wind conditions caused the spray to visibly impact outside the cell. Sub-

limation from the snowpack is also probably small, but has not been measured. The formation of aerosols undoubtedly occurs to some extent, but the pressure at the nozzle is low, so mean droplet size is expected to be rather large. The measured differences are thus mainly due to plant evapotranspiration. A ballpark figure of 80% of pan evaporation is often used to estimate plant evapotranspiration (Linsley et al. 1958). The values obtained in this study range from 86 to 117% with a mean value of 105%. It appears that the 80% value is too low for slow rate systems, at least in the northeast United States.

If the "missing" water was mainly due to plant evapotranspiration, we felt a correlation should exist between the amount of missing water and the amount of plant material produced. For cells 1 and 6, both the water balances (Appendix Tables A1 and A6) and plant yields (Jenkins et al. 1981) are available from June 1974 through May 1980. For cells 2-5 the water balances are available throughout (Appendix Tables A2 through A5), but yield measurements were only available from June 1974 through May 1978 (Jenkins et al 1981). These results have been tabulated in Table 14.

The amount of missing water per kilogram of dry matter produced ranged from 979 to 1228 L/kg with a mean value of 1049 L/kg. With the exception of cell 2, this ratio for the other five cells was very similar. Thus slightly more than 1000 L of water was lost from the test cells for every kilogram of dry matter (forage grass) produced. This value is somewhat higher than those for other crops such as lucerne (alfalfa), corn, wheat, rice and flax, which have been reported to use from 277 to 844 L of water/kg of dry matter produced (Mengel and Kirkby 1978).

Table 14. Yield of plant material produced versus amount of "missing" water.

Test cell	Yield (kg dry wt)	Missing water (L)	Ratio (L/kg)
1*	273 59	288,702	1055
2†	166 37	204,251	1228
3†	151 51	153,744	1015
4†	147 67	150,372	1018
5†	175 81	176,060	1001
6*	281 16	275,645	979

*Data obtained from June 1974 through May 1980

†Data obtained from June 1974 through May 1978

Mass balance of N

The design of the CRREL test cells is uniquely suited to provide information on the relative importance of plant uptake, leaching of nitrate N, and the sum of various other mechanisms that remove N. The concentration of N applied to and percolating from the test cells has been carefully monitored from June 1973 through May 1980 for cells 1 and 6, and from June 1973 through May 1978 for cells 2-5. We have measured the volume of water associated with each analysis since June 1974 and have also calculated the amounts of N removed by the forage grasses. These results (Table 15) allow an accurate assessment of the fate of applied N.

The amount of N applied to test cells 1 and 6 from June 1974 through May 1980 and to cells 2-5 from June 1974 through May 1978 ranged 2440 to 4293 kg/ha. The mean N content of rainfall in Hanover, New Hampshire, has been studied and found to be about 0.3 mg/L-N as nitrate and 0.2 mg/L-N as ammonium (Dr. J.F. Hornig, Dartmouth College, pers. comm.). This

value agrees well with published results from the Hubbard Brook Research Study (Eaton et al. 1978). These concentrations have been multiplied by the rainfall volumes to calculate the mass of N in the rainfall in kg/ha. These values were added to the wastewater N to give the total N applied to the cells over the study period (Table 15). Fixation of N by the test cell soils and plants has been assumed to be zero, primarily because of the highly mineral-rich environment and the types of plant species grown.

Plant uptake of N ranged from 1063 to 2050 kg/ha. The N that percolated through the soil profile was mainly nitrate and ranged from 957 to 2557 kg/ha. The amount that percolated from a specific test cell was a function of the average application rate used.

When the amount of N taken up in the grass and the amount that leached in the percolate are subtracted from the total amount applied, 72 to 507 kg/ha remains unaccounted for (Table 15). This amount is from 2.9 to 14.4% of the total N applied. By considering only plant uptake and the leaching of N from the profile, an average of 91% of the applied N has been accounted for over a 4- or 6-year period. The amount of N remaining can be attributed to the sum of all other renovative mechanisms such as denitrification, ammonia volatilization from the soil, and net storage of N in the soil. The volatilization during sprinkler application is not considered here since the N applied is calculated from the samples taken at the soil surface.

Denitrification and removal mechanisms other than plant uptake and leaching account for only about 9% of the N applied. This is significantly lower than the 20% assumed by the Process Design Manual for the Land Treatment of Wastewater (EPA 1977). This result agrees with conclusions obtained by Brar et al. (1978) and Kissel et al. (1979). Brar's results, from the Penn-

Table 15. Total N mass balance (kg/ha), June 1974 through May 1980.

Test cell	Applied	Precipitation	Total	Plant uptake	Percolate	Percent† removal	Missing	Percent missing
1	3474	40	3514	2050	957	72.5	507	14.4
2*	4293	30	4323	1359	2557	40 4	408	9.4
3*	2477	30	2507	1149	1148	53.7	210	8.4
4*	2443	30	2473	1063	1222	50.0	188	7 6
5*	2440	30	2470	1232	1166	52 2	72	2 9
6	3550	40	3590	1991	1112	68 7	487	13 6

*Data for these cells only available through May 1978
†Removal efficiency for percolate vs applied wastewater

sylvania State University system, indicated a lack of significant potential for denitrification, probably due to an insufficient source of organic C for the denitrifying organisms. The CRREL test cells are also low in organic C due to the low levels of C in the wastewater and the initial low levels in the soils (Table 3). Kissel's results, from agricultural fertilization of coastal bermuda-grass over a 6-year period, indicate that N losses due to denitrifications were insignificant.

Seasonal N variation in percolate

The average concentration of percolate nitrate ranged from 6.4 mg/L in cell 1 to 13.2 mg/L in cell 2 (Table 16). The annual mean concentration of nitrate in the percolate was found to correlate well with the annual total N loading rate (Fig. 7). Long term application of wastewater at a rate of 5 cm/wk resulted in mean percolate nitrate concentrations of 6.4 mg/L in the Windsor soil and 6.6 mg/L in the Charlton soil. Wastewater was applied at a rate of 7.5 cm/wk from 1974–76, with average mass loadings of about 800 kg/ha that resulted in percolate nitrates of about 9 mg/L. For these total N loading rates and the best fit line in Figure 7, a value of about 10 mg/L would be predicted. An application rate of 7.5 cm/wk thus seems feasible for a wastewater with a mean total N content of about 25 mg/L, if

Table 16. Mean N content of percolates.

| Test cell | N (mg/L) | | | |
	Nitrate*	Ammonium	Organic	Total
1†	6.4 (557)	0.1 (517)	0.8 (219)	7.3
2**	13.2 (540)	1.4 (504)	0.3 (243)	14.9
3**	9.0 (515)	0.8 (479)	0.4 (232)	10.2
4**	9.7 (512)	<0.1 (479)	0.1 (235)	9.8
5**	9.4 (470)	<0.1 (433)	0.1 (204)	9.5
6†	6.6 (562)	<0.1 (518)	0.7 (236)	7.3

* Values in parentheses refer to the number of individual analyses which are represented by the mean value.
† June 1973 through May 1980.
** June 1973 through May 1978.

a mean percolate nitrate limit of 10 mg/L is the performance criterion to be met.

The nitrate concentrations in the percolate of the six test cells varied on a seasonal basis. Figure 8 presents monthly mean values for test cells 1 and 6 between June 1973 and May 1980. The concentrations of nitrate were generally lower in these two cells than in the other four cells due to a lower wastewater application rate, 5 cm/wk over the entire 6-year period. Cell 1 contains Windsor soil; cell 6 contains Charlton soil. We applied secondary wastewater to both through
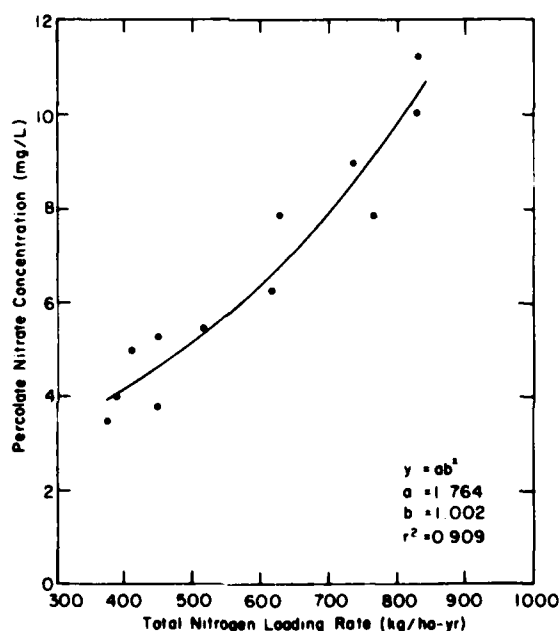
Figure 7. Percolate nitrate concentration vs annual N loading rate, test cells 1 and 6, June 1974 through May 1980.
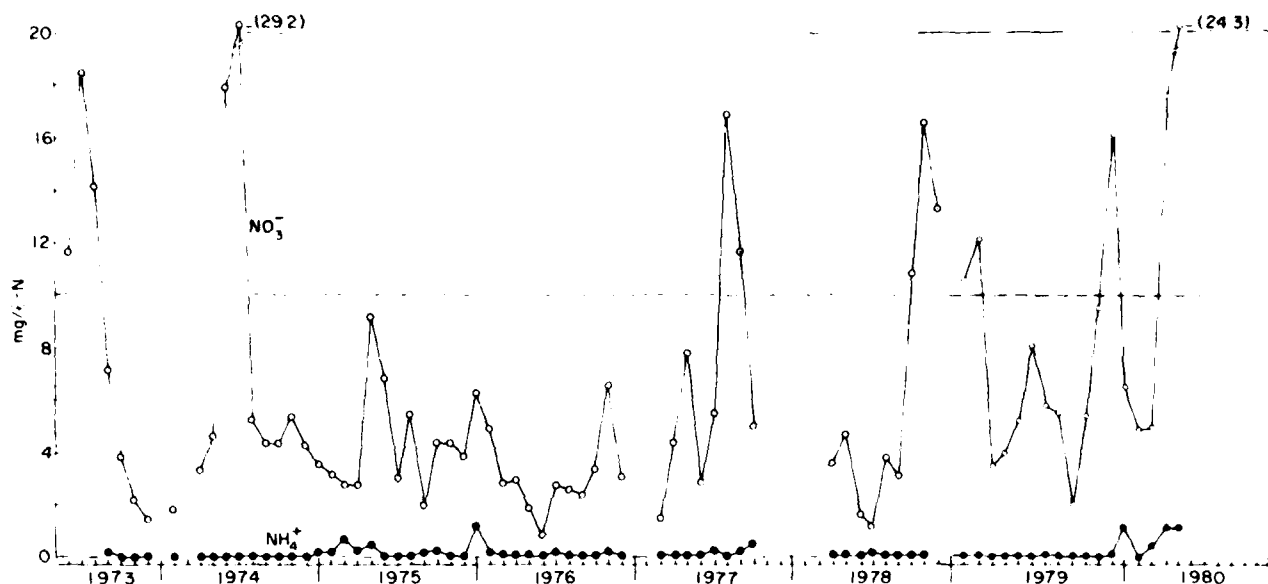
a. Test cell 1.
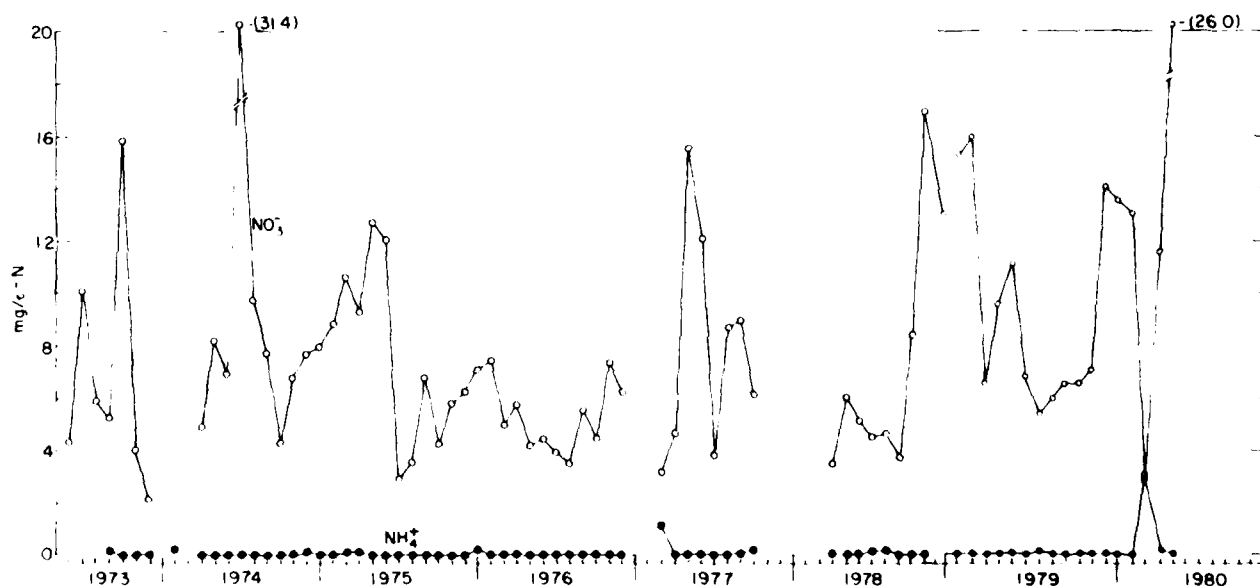
b. Test cell 6.

Figure 8. Monthly averaged nitrate and ammonium in percolate from cells 1 and 6, June 1973 through December 1980.

August 1978, then applied primary wastewater through 1980.

We found high concentrations of nitrate in the percolate from these cells in early summer 1974, following the first year of wastewater application (Iskandar et al. 1976). The values averaged about 30 mg/L for both cells in July 1974. Nitrate concentrations have never again approached these levels in 6 subsequent years, although a peak of higher than normal concentrations did occur nearly every summer for all six test cells.

The unusual intensity of the nitrate peak in 1974 may be characteristic of the first year of wastewater application. Reinholm and Avni-melech (1974) and Cole and Scheiss (1978) found similar behavior during the first year of waste-

23
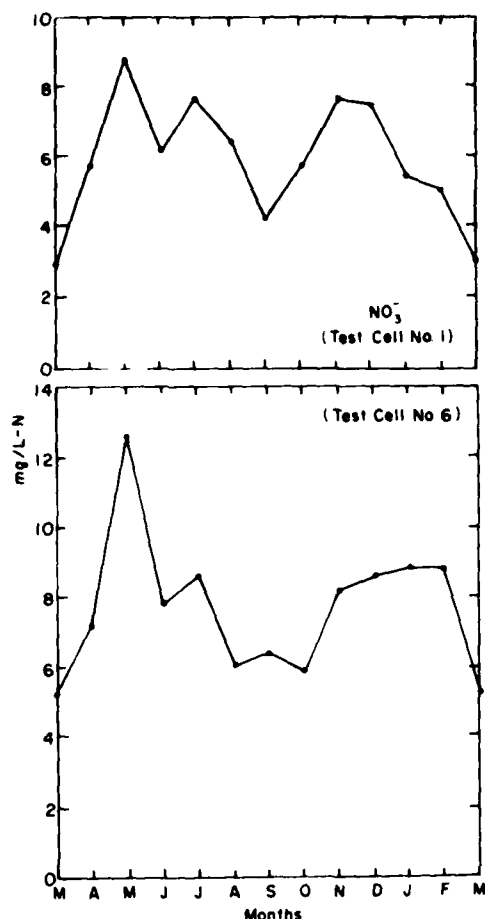
Figure 9. Average annual cycle of percolate nitrate in cells 1 and 6.

water application to soil. Increased mineralization of native soil N presumably causes this phenomenon.

Since the first year, concentrations of nitrate in the percolate have generally remained below 10 mg/L for these two cells. Occasionally, monthly mean values have exceeded 10 mg/L but they always stayed above 10 mg/L for less than 2 months. It should be emphasized that the concentrations measured are not diluted with natural groundwater as they would be in real systems even before the water left the system boundary. In a real system, the concentrations would be diluted before the water was available for reuse.

Figure 9 shows the average percolate values for each month (an average annual cycle). This cycle shows two peaks in the nitrate concentration for both cells 1 and 6, one in early summer

and the second in early winter. Because of the travel time or detention time in the soil profile, estimated to be about 2 or 3 months (Fig. 6), the water leaving the 152-cm profile during these two periods passed through the plant rooting zone up to several months before emerging as percolate. These high nitrate concentrations correspond to periods of wastewater application before and after the major plant growing season. Hence a substantial portion of the N applied during these periods leached through the soil.

A curious phenomenon was observed when wastewater was applied to cells 1 and 6 in the winter of 1974-75 and to cell 6 in the winter of 1975-76 (Fig. 8). Much of the ammonium applied during these periods was not totally nitrified since ammonium moved through the entire profile in cell 1 and was found in the percolate at low concentrations (Fig. 8) (Iskandar et al. 1976) We observed this phenomenon to a much larger extent in cell 2 during the winter of 1974-75 and will discuss it later. Some nitrification did occur throughout the winter, however, as shown by the continued presence of nitrate in concentrations as high as 10 mg/L in the percolate throughout these periods. No large peak of nitrate was found in the percolate in the spring or summer following these winter applications. The fate of the N stored in the soil during winter applications is unclear. Ammonium that had slowly moved downward in the profile during winter may have nitrified at a slow rate thereafter. The nitrate formed would leach over long periods and not show a large peak in concentration in the months following winter application.

Test cells 3 and 4 were treated with primary wastewater from June 1973 through May 1978, with annual variation in the wastewater application rate of 5 to 11 cm/wk (Table 1) Cell 3 was filled with Windsor soil, cell 4 was filled with Charlton soil. Both cells were treated in an identical manner to assess variations in response due to different soil types. The mean percolate N content from cell 3 was 10 2 mg/L, that from cell 4 was 9.8 mg/L. In both cases, the percolate N was almost totally in the nitrate form (Table 16)

Figure 10 shows the seasonal behavior of nitrate in the percolate from cells 3 and 4. As in cells 1 and 6, a high peak of nitrate concentrations was generally found for cell 3 in early summer each year. This same peak was observed in cell 4 as well, generally a little later because the Charlton soil retained wastewater longer.

In June 1976 the surfaces of cells 2-5 were reconditioned to level the irregularities in the sur-

24
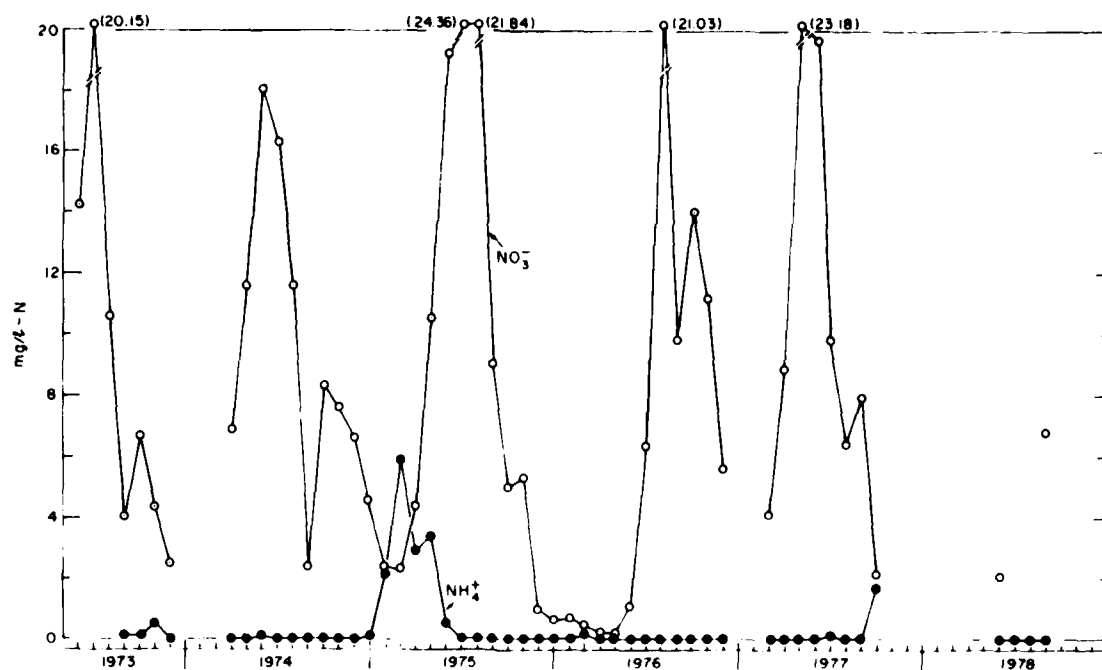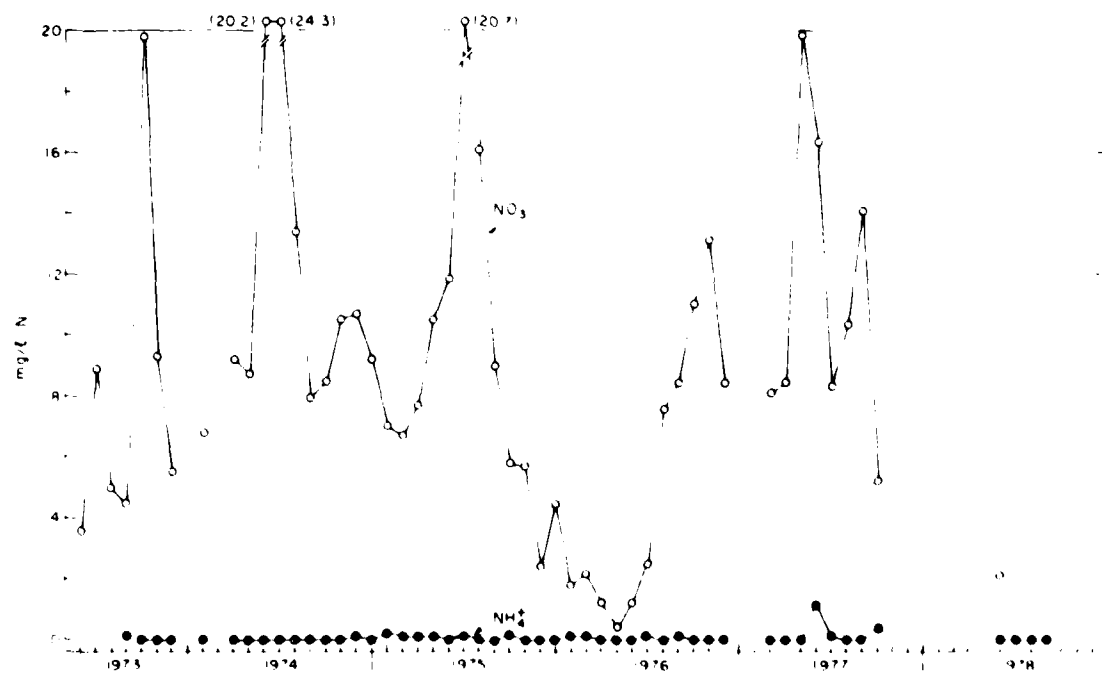
a. Test cell 3.

b. Test cell 4.

Figure 10 Monthly averaged nitrate and ammonium in percolate from cells 3 and 4, June 1973 through December 1978.

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Table 17. Test cell 3 and 4 annual percolate N.

Period	Application rate (cm/wk)	Percolate N (mg/L) Test cell 3	Percolate N (mg/L) Test cell 4
June 1973-May 1974	5	9 1	7 9
June 1974-May 1975	7 5	8 8	11 1
June 1975-May 1976	7 5	10 4	8 6
July 1976-May 1977*	2 5 11†	11 6	9 4
June 1977-May 1978	7 5	9 7	10 4

* Cells reconditioned in June 1976
† The application rates were changed periodically in an attempt to match seasonal plant uptake

face of the cells caused by soil settling after construction. At this time quackgrass was the dominant vegetation in the test cells; reconditioning also provided a good opportunity to establish a more desirable forage species such as orchardgrass or reed canarygrass. Reconditioning included rototilling the surface soil to a depth of 15 cm and reseeding. Wastewater irrigations were resumed in July 1976 and continued through the fall. The percolate concentrations from cells 3 and 4 were high for a period of about a year following this reconditioning process, roughly the same behavior found during the first year wastewater was applied to the cells. The growth of vegetation was slow during this establishment period and plant uptake of N was lower than usual. Loading rates of wastewater should therefore be reduced during the initial year of wastewater application and after site reconditioning to maintain percolate N at acceptable levels.

Table 17 presents the annual percolate N resulting from various application rates of primary wastewater on test cells 3 and 4. Application rates of about 7.5 cm/wk resulted in average percolate values of about 10 mg/L, the federal drinking water limit for nitrate.

The peaks of nitrate concentration exceeded 20 mg/L, generally for short periods in the early summer. The dilution that occurs when this leachate mixes with the natural groundwater would reduce the effect of these short term fluctuations in actual operating land treatment systems. A 7.5-cm/wk application rate may therefore be acceptable for these soils. No large differences in performance due to soil types were observed.

The annual application rates and percolate N concentrations are given for test cells 2 and 5 in Table 18. These cells received various application rates and types of wastewater. Test cell 2 contained a Windsor soil and received 15 cm/wk of secondary effluent at a rate of 5 cm/day, 3 days a week over a 2-year period from June 1974 through May 1976. The percolate N resulting from this high wastewater loading rate exceeded 10 mg/L most of the time. This 15 cm/wk application rate was used throughout the winter of 1974-75 and resulted in the leaching of not only nitrate but also ammonium from the bottom of the profile (Fig. 11). Iskandar et al. (1976) found monthly average concentrations of ammonium as high as 9.5 mg/L in March 1975. When the 15 cm/wk application rate was continued in 1975-76, applications were suspended during winter and no significant leaching of ammonium was found. The movement of ammonium through the profile in the Windsor soil (cells 1 and 2) probably resulted from the low cation exchange capacity (7 meq/100 g) of this soil. Even after two winter applications on cell 6, no leaching of ammonium was found for this cell, which contains

Table 18. Test cell 2 and 5 annual percolate N.

Period	Test cell 2 Application rate (cm/wk)	Test cell 2 Percolate N (mg/L)	Test cell 5 Application rate (cm/wk)	Test cell 5 Percolate N (mg/L)
June 1973-May 1974	10-S†	10 9	10-S	9 3
June 1974-May 1975	15-S	16 4	7 5-P (24 hr)	12 0
June 1975-May 1976	15-S	15 5	7 5-P (24 hr)	5 8
July 1976-May 1977*	2 5-12-P‡	12 5	2 5-11-P	9 4
June 1977-May 1978	7 5-P	10 11	7 5-P	12 3

* Surface of cells reconditioned in June 1976
† S — secondary wastewater
‡ P — primary wastewater
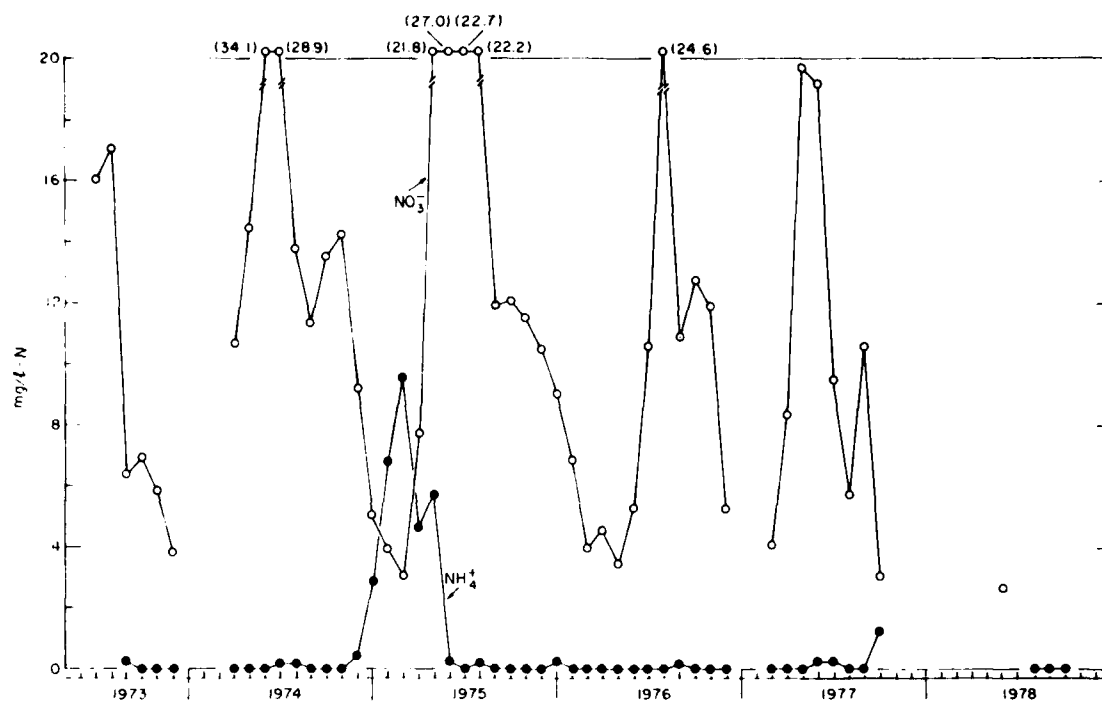
a. Test cell 2.
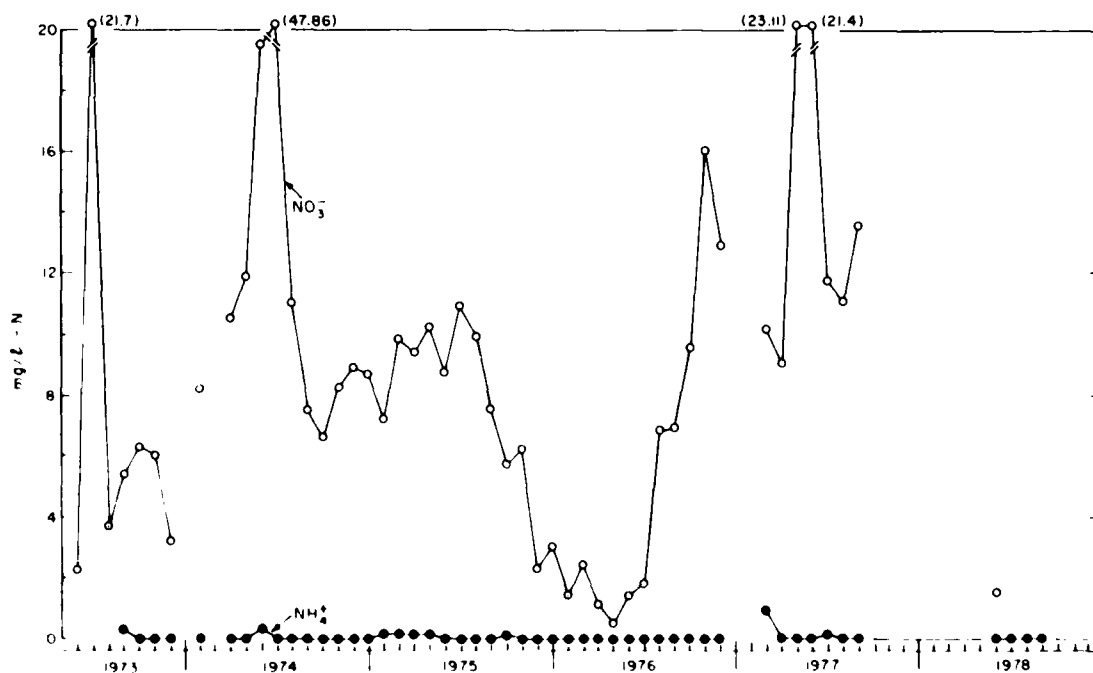
b. Test cell 5.

Figure 11. Monthly averaged nitrate and ammonium in percolate from cells 2 and 5, June 1973 through December 1978.

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the Charlton silt loam soil. The cation exchange capacity for the Charlton soil is 13.5 meq/100 g, so this soil can retain considerably more ammonium than can the Windsor soil.

Table 18 gives the annual loading rates of wastewater applied to cell 5 along with the resulting percolate total N concentrations. Figure 11 shows the seasonal behavior of percolate nitrate during the period of wastewater application. In the other cells we found very high concentrations in the early summer following the first year of application. Since that time we have observed only one incident in which nitrate has reached 20 mg/L. That incident was in May–June 1977 after the surface reconditioning.

From June 1974 through May 1976, cell 5 received 7.5 cm of wastewater per week in one 24-hr application. This schedule compares with cell 4 where the same weekly loading rate was used, but where the application was spread over three 8-hr periods on consecutive days. We compared the mean percolate N concentrations resulting from these application schedules from September 1974 through May 1976. The results showed a mean percolate nitrate concentration of 8.9 mg/L for cell 5 and 10.6 for cell 4. The application of the wastewater in one 24-hr period seems to have slightly improved the N treatment relative to the application of the same volume in three 8-hr periods on three consecutive days. This conclusion differs somewhat from that presented by Palazzo and McKim (1978) for this same experiment. These investigators did not consider the travel time necessary for water applied at the surface to percolate through the 152-cm profile. Nitrogen concentrations from June 1974 through August 1974 were included in their calculations although they are mainly a result of the application schedule used on the cells the previous year. In the previous year, cell 5 received 10 cm of wastewater per week while cell 4 received only 5 cm. Percolate nitrates were therefore expected to be somewhat higher for cell 5 during these 3 months and were found to average 23.8 mg/L, compared to 19.0 mg/L for cell 4 during this time.

The reason for improved performance when the water is applied in one continuous 24-hr application period is uncertain. One possible explanation is that the ammonium applied, when applications are made in three 8-hr periods on consecutive days, nitrifies in the rest periods between applications The nitrate formed is much more mobile in the soil than is ammonium A portion of this nitrate could leach beyond the ef-

fective rooting zone of the plants with the next application, leaving less available for plant uptake. If a large portion of the N applied in the wastewater was already in the nitrate form, three consecutive 8-hr applications would probably be superior to one 24-hr application.

Plant yields and N uptake

As shown in Table 15, plant uptake was found to be the major mechanism for removal of N. In order to determine the relationship between the amount of N applied and the amount removed by the grass, the mass of N applied after the last harvest period each year through the last harvest period the following year was plotted versus the amount of N removed by the crop over this period. The results are shown in Figure 12.

For the most part a relatively linear relationship was obtained for loading rates of N up to about 800 kg/ha. In this range about 60% of the applied N is taken by the grass. Above 800 kg/ha, the curve breaks and there is very little increase in N uptake for large increases in N loading. To obtain the best fit, the eight points obtained for 1975 and 1976 were neglected since analysis indicated that during these years the soils and plants were K deficient (Palazzo and Jenkins 1979) and hence these results are not typical of optimum growing conditions. During these years plant K levels were found to average 2.16% with individual values as low as 1.45% as compared to an average of 3.05% found in other years.

These plant uptake results agree well with the percolate nitrate relationship given in Figure 7 This figure shows that above 800 kg/ha the percolate nitrate concentrations increase significantly. This coincides with the breakpoint in the plant uptake curve above which the plants are unable to maintain the high percent removal found below 800 kg/ha.

Plant yields during the study were found to range from 7.4 to 17.6 metric tons/ha with a mean value of 13.1 metric tons/ha. The yield was found to be related to N loading rate in the same manner as shown for N uptake (Fig. 12). The average yield was about three times as great as the yield from a normal hayfield in this area (N.E.C.L.R. 1978), indicating a very favorable response of the grass to the applied wastewater.

Periodic samples of the grass were analyzed to determine its suitability as animal feed. The results indicated it was of excellent quality (Barnes 1975). The grass was found to contain an

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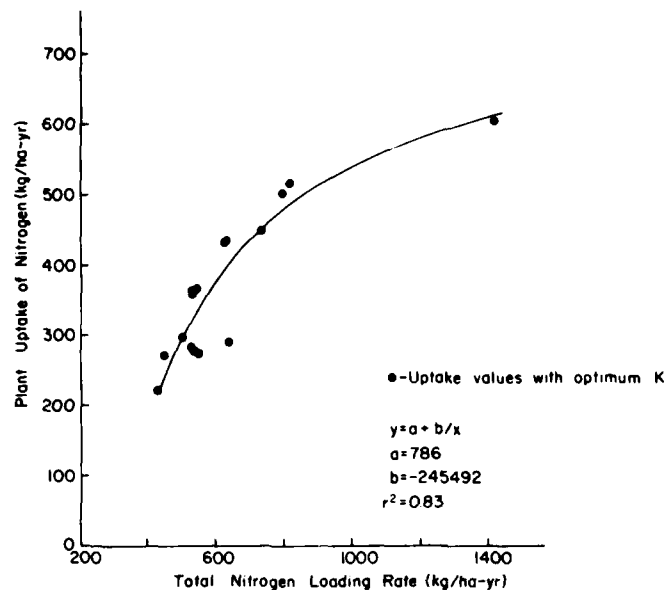
Figure 12. Plant uptake of N vs annual wastewater N loading rate.

average of 20% crude protein and 63% total digestable nutrients.

In terms of cost benefits to a land treatment system the value of the hay can be calculated on a 15% moisture basis. The average hay yield was 13.1 metric tons/ha on a dry weight basis or 15.1 metric tons/ha on a 15% moisture basis. When considering 66 kg bales at $1.50/bale, the annual value of this hay is about $343/ha.

Plant uptake by harvest periods

Table 19 presents the average amount of N removed by the plants in cells 1 and 6 during each harvest period from 1974 through 1980. Cells 1 and 6 received 5 cm/wk of wastewater through-

out this period. Information on plant uptake of N for periods of less than a year is required by some designers of land treatment sites. The *Process Design Manual for Land Treatment of Municipal Wastewater* (EPA 1977) requires system design calculations on a monthly basis.

In this study the first harvest period was the most active in terms of average daily uptake of N. Although the number of days in each successive period increased, total and mean daily plant uptake declined for each successive harvest period. Of the total annual amount of N taken up by plants, an average of 38% was removed during the first harvest, 34% in the second harvest, and 28% in the third harvest. Palazzo and Graham

Table 19. Average plant uptake of N by harvest periods for cells 1 and 6 (1974 through 1980).

Cutting	Actual (kg/ha)	Percent of annual total	Mean daily uptake (kg/ha)	Average no. of days in harvest period
First*	149 6 ± 48 6	38	4.04	37
Second	132 0 ± 51 1	34	2 81	47
Third†	107 8 ± 55 7	28	1 66	65

* The first cutting period was assumed to begin on 1 May
† The third period ended at the last cutting of the year, generally in mid-September

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(1981), who studied the seasonal growth of orchardgrass under similar conditions in Hanover, also reported a decline in daily plant uptake of nutrients for each successive harvest period.

Phosphorus treatment

During the 7-year period, June 1973 through May 1980, the total P applied to the test cells varied from 859 to 1531 kg/ha (Table 20). The concentration of total P in the primary wastewater during the first 5 years averaged 7.6 mg/L; that in the secondary wastewater averaged 7.3 mg/L (Table 8). The concentration of total P averaged 6.9 mg/L for the primary wastewater from June 1978 through May 1980 (Table 9).

From the beginning of the experiment, June 1973, through May 1975, the percolate from the test cells was analyzed for total P with a digestion procedure. This method had a detection limit of about 0.2 mg/L. In all cases the concentration of P in the percolate was found to be below this detection limit.

From June 1975 through May 1980, the percolate was also analyzed for ortho-P using a method with a much lower detection limit (about 0.01 mg/L). The mean percolate ortho-P concentrations over this period ranged from 0.03 mg/L in test cell 6 to 0.07 mg/L in test cell 2. Only one single monthly average value over this period for any one cell ever exceeded 0.14 mg/L. The mean percolate concentrations were found to be slightly higher in cells where higher average loading rates of P were used, but the increase was small compared to the increased P loading. This is particularly evident for cell 2, which had a much higher P loading rate. Because the concentration of P was below the detection limit of the analytical method used for the first 2 years, the percent of mass removed cannot be accurately calculated. If we assume the average P concentrations in the test cell percolates were equal in the first 2 years to those measured since 1975, we can calculate mass removal percentages (Table 20). When this was done, mass removals ranged from 98.9 to 99.5%. While the mass removal calculations are based on low level ortho-P measurements on the percolate, organic C and organic N measurements indicate that very little organic P could be leaching.

Figure 13 presents monthly averaged ortho-P concentrations for cells 1 and 6. Percolate phosphate concentrations were not found to be seasonally dependent. Monthly values for test cells 2-5 are similar.

The removal of P from solution as the water percolates through the soil is due to soil reactions and plant uptake. Table 21 presents the amount of P taken up by the plants over the 7-year study period. The 7-year mean plant uptake ranged from 18 to 30% of total P applied over this period and the mass uptake ranged from 29 to 39 kg/ha. Plant uptake of P was not a function of application rate.

When mass loading rates of P were below 75 kg/ha, plants removed over 50%. Similar results have been reported by Clapp et al. (1978) in a review paper covering forage grasses receiving secondary wastewater at five sites in the U.S. and Canada. Hook et al. (1974) and Karlen et al. (1976) have also found similar results.

Table 20. Test cell P removal (June 1973 through May 1980).

Test cell	Average application rate (cm/wk)	P applied†		P in percolate		Removal (%)
		Conc (mg/L)	Total (kg/ha)	Conc* (mg/L)	Total† (kg/ha)	
1	5	7.5	913	0.04	6.4	99.3
2**	11	7.9	1531	0.07	15.2	99.0
3**	7	8.3	859	0.05	7.3	99.2
4**	8	7.7	878	0.06	8.5	99.0
5**	8	7.7	878	0.06	8.5	99.0
6	5	7.3	1101	0.03	5.0	99.5

* Percolate ortho-P concentrations reported are for the period June 1975 through May 1980 for cells 1 and 6 and June 1975 through May 1978 for cells 2-5.

† Assuming concentration of P in percolate before June 1975 was similar to that measured in the period 1975 through 1980.

** Data reported covers the period June 1975 through May 1978.
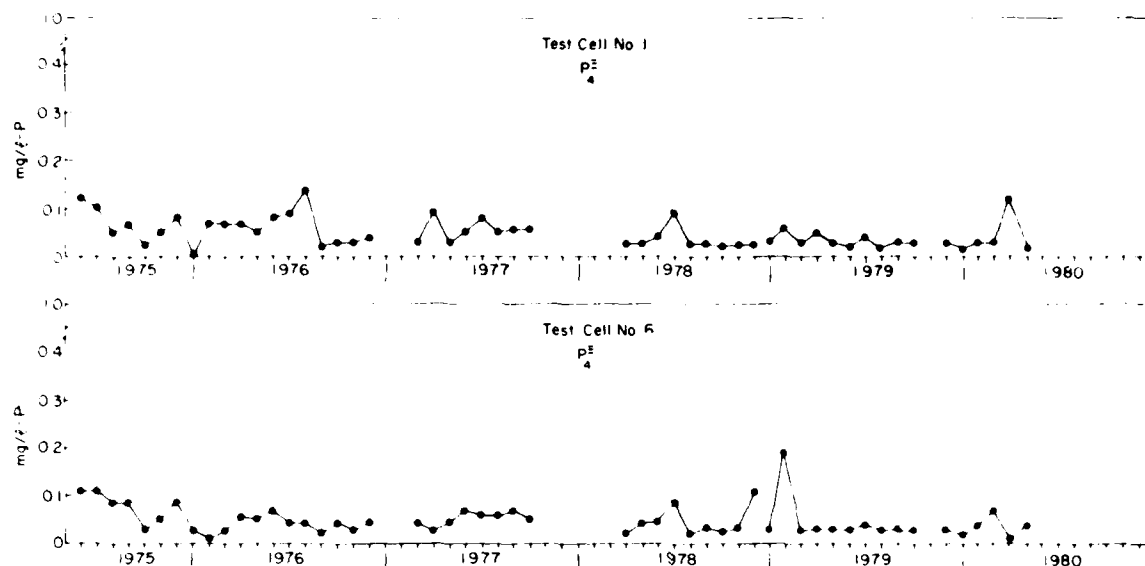
Figure 13. Monthly average ortho-P concentrations in test cell 1 and 6 percolates.

Table 21. Total annual application and plant uptake of P (kg/ha), June 1973 through May 1980.

	Cell 1			Cell 2			Cell 3			Cell 4			Cell 5			Cell 6		
	Appl	Plant uptake	% removed by plants	Appl	Plant uptake	% removed by plants	Appl	Plant uptake	% removed by plants	Appl	Plant uptake	% removed by plants	Appl	Plant uptake	% removed by plants	Appl	Plant uptake	% removed by plants
June 73-May 74	168	29	17	446	34	8	179	25	14	181	30	17	288	33	11	168	32	19
June 74-May 75	208	40	19	624	53	8	320	42	13	319	40	13	297	43	14	199	27	14
June 75-May 76	108	33	11	256	32	12	111	23	21	105	24	23	155	26	23	140	33	24
June 76-May 77	102	33	32	107	26	24	101	20	20	102	25	25	124	30	24	104	49	48
June 77-May 78	78	50	64	98	35	36	147	36	24	66	37	56	55	36	65	71	52	73
June 78-May 79	112	52	46	−	−	−	−	−	−	−	−	−	−	−	−	115	41	36
June 79-May 80	118	34	25	−	−	−	−	−	−	−	−	−	−	−	−	118	23	17
Total	914	271	30	1531	180	18	858	146	17	773	156	20	879	168	19	915	247	26
7-year mean	131	39	30	306	36	18	172	29	18	155	31	20	176	34	19	134	35	26

A study conducted by Overman and Ku (1976) indicates that forage grasses remove P more efficiently than do cereal crops and Kardos and Sopper (1974) found that forages are more efficient than corn. Since the crops used in the test cells were forage grasses, a change to another type of vegetation would probably not improve P removal. If P loading rates are in excess of 75 kg/ha/yr, the soil must be relied on to remove a major portion of the P and to do so for long periods. While plant uptake at these higher loading rates accounts for only a small percentage of the P applied (Table 22), it may extend the system's lifetime by lessening the amount of P the soil must assimilate.

Since the bulk of P applied to the test cell was not found in either the percolate or in plant material, it has accumulated in the soil. For the six cells this accumulation ranges from 600 to over 1300 kg/ha. The soil was analyzed at depth for total P initially and periodically through 1980. The results for cells 1 and 6 are presented in Figure 14.

For cell 1, a significant increase in soil P was found in the upper 30 cm of soil while little change was found deeper in the profile. This result is consistent with analyses of soil solution and percolate which indicate very little downward movement of P (Table 23). When tabulated on a mass basis, this change is roughly equivalent to the mass of P applied to cell 1, but not found in percolate or plant analysis.

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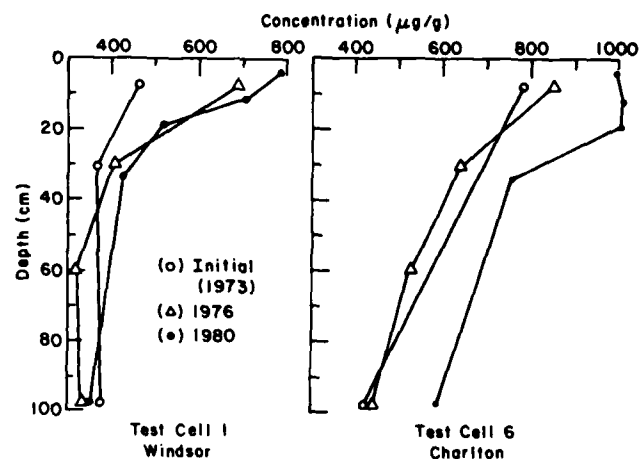
Figure 14. Soil P concentrations for test cells 1 and 6.

Table 22. Mean plant removal of P under various mass loadings.

Range of P loading rate (kg/ha/yr)	Mean loading rate (kg/ha/yr)	Mean removal (kg/ha/yr)	No. of determinations*	Plant uptake (%)
0–75	68	40	8	59
75–150	107	41	11	38
Above 150	230	48	5	21

* Number of determinations within the appropriate mass loading range for P

Table 23. Mean ortho-P concentrations (mg/L) in soil solution at 45 cm and in the percolate.

	Test cell 1 (Windsor)		Test cell 6 (Charlton)	
	45 cm	Percolate*	45 cm	Percolate*
1975	0.08 (7)†	0.07 (41)	0.08 (17)	0.05 (40)
1977	0.15 (2)	0.05 (36)	0.05 (18)	0.04 (36)
1978	—	0.02 (22)	—	0.02 (22)
1979	—	0.04 (30)	—	0.04 (26)
1980	—	0.03 (32)	—	0.03 (32)

* Some values for percolate (152-cm depth) were taken from Jenkins et al. (1978).
† Numbers in parentheses are the number of individual analyses.

The results for cell 6 show a similar increase in soil P in the upper 30 cm of the profile. The 1980 analysis at 100 cm, however, indicates a significant rise in soil P deeper in the profile. This result is not consistent with the 1976 result nor with the analyses of soil solutions and percolate (Table 23). When tabulated on a mass basis, a much larger increase in soil P than the mass of P applied over this period is indicated. Thus we feel the 1980 result for 100 cm is not representative of the average P concentration at that depth. More analysis of soil samples will be required to resolve this inconsistency. However, after 7 years of wastewater application, we found no indication that treatment of P had declined or is likely to do so in the near future.

Treatment of other major constituents

While much of our attention was focused on the effectiveness of N and P removal, a thorough understanding of slow rate irrigation systems also requires a knowledge of the efficiencies with which it removes other constituents. Some of the more important are oxygen demanding substances such as BOD_5, total organic C (TOC), suspended matter (TSS), bacterial indicator organisms such as fecal coliform bacteria and fecal streptococci, viruses, heavy metals, and trace organics. Since June 1974, BOD_5, total and volatile suspended solids, and fecal coliform

bacteria have been periodically measured. From June 1979 through May 1980 measurements of fecal streptococci and low level total organic C were also obtained. These values are given in Table 24. A study of virus transport was conducted in the fall of 1975 and 1976 by the U.S. Army Medical Bioengineering Research and Development Laboratory and will be reported on in Schaub and Bausum (in prep.).

The mean BOD_5 concentrations in the percolate ranged between 0.9 and 1.7 mg/L with the values from cells 4–6, which had the finer textured Charlton soil, being slightly lower. On a mass basis, the system removed 96 to 98% of the applied BOD_5. There was no correlation between the percolate BOD_5 and the wastewater loading rate or the degree of preapplication treatment, indicating that for BOD_5 treatment, even at the highest application rate of 15 cm/wk, the cells were underloaded. Only in the final year of the study were precise total organic C measurements made for percolates from test cells 1 and 6. The values ranged from 1.0 to 3.0 mg/L with mean values of 1.9 and 1.8, respectively. Measurements of organic C in previous years were obtained by a much less precise method, but there is some indication that levels have tended to decrease as applications have continued (Jewell and Bouzoun, in prep.).

The removal of suspended solids was found to

Table 24. Performance of test cells for BOD_5, suspended solids, fecal coliform, fecal streptococci and organic carbon (June 1974 through May 1980).

Test cell	BOD₅ (mg/L) Applied	BOD₅ (mg/L) Percolate	Total suspended solids (mg/L) Applied	Total suspended solids (mg/L) Percolate	Volatile suspended solids (mg/L) Applied	Volatile suspended solids (mg/L) Percolate	Fecal coliform bacteria (no./100 mL) Applied	Fecal coliform bacteria (no./100 mL) Percolate	Fecal streptococci bacteria‡ (no./100 mL) Applied	Fecal streptococci bacteria‡ (no./100 mL) Percolate	Total organic carbon‡ (mg/L) Applied	Total organic carbon‡ (mg/L) Percolate
1	59	1.3 (97%)†	81	0.8 (99%)	51	0.5 (99%)	3.1×10^5	0 (100%)	2.4×10^5	1 (100%)	101	1.9 (98%)
2**	40	1.5 (96%)	70	1.5 (98%)	50	0.3 (99%)	1.2×10^4	0 (100%)	—	—	—	—
3**	92	1.7 (97%)	96	0.9 (99%)	75	0.4 (99%)	2.2×10^5	1 (100%)	—	—	—	—
4**	91	1.4 (98%)	85	1.0 (98%)	62	0.6 (99%)	2.2×10^5	0 (100%)	—	—	—	—
5**	86	1.1 (98%)	58	2.2 (95%)	39	1.1 (97%)	2.4×10^5	109* (99.9%)	—	—	—	—
6	57	0.9 (98%)	78	0.9 (99%)	50	0.3 (99%)	3.1×10^5	0 (100%)	2.0×10^5	0 (100%)	101	1.8 (98%)

* This high value is a result of poor soil compaction in the construction of this cell
† Numbers in parentheses are percent removals by mass
‡ Data obtained from June 1979 through May 1980 with primary undisinfected wastewater
** Data obtained from June 1974 through May 1978

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be as good as that for BOD_5. The residual concentrations in the percolate ranged from 0.8 to 2.2 mg/L for total suspended solids with a mass removal of 95 to 99% and 0.3 to 1.1 mg/L for volatile suspended solids with a mass removal of 97 to 99%. As with BOD_5, no correlation was found between suspended solids in the percolate versus wastewater loading rate.

These prototypes remove BOD_5 and suspended matter more effectively than any advanced wastewater treatment technique currently available. The use of a secondary treatment step prior to land application did not improve the quality of the percolating water with respect to these parameters and is probably unnecessary.

The coliform group of bacteria has traditionally been used as the principal indicator of the bacteriological suitability of waters for domestic use. While this method has been questioned, no alternative has been universally accepted. Fecal coliform measurements of the leachate from the test cells have been taken periodically over the period June 1974 through May 1980. More than 400 individual analyses were run over this period and, except for cell 5, the results were generally below detectable limits (Table 24). The wastewater applied was disinfected with ozone part of the time. Frequently, however, undisinfected wastewater was applied during periods when the ozonator was malfunctioning. The primary and secondary wastewater averaged 2×10^5 and 1×10^4 organisms per 100 mL over the first 5 years of the study (Table 8). The percolate quality was not improved by secondary treatment or disinfection prior to application. As a result, we applied totally undisinfected primary wastewater to test cells 1 and 6 from June 1978 through May 1980. The average wastewater fecal coliform and fecal streptococci levels average 8.4×10^5 and 2.4×10^5 (no./100 mL), respectively, but no organisms were detected in the percolate.

The results obtained for cell 5 were quite different (Table 24). Fecal coliform bacteria were found frequently in the percolate from this cell in numbers as high as 4000 organisms per 100 mL. The reason for this behavior was unclear until a small cavity was found just under the surface that extended deep into the 1.5-m profile. This cavity was located while taking soil cores for analysis and was apparently formed by poor compaction during construction. It should be recalled, however, that the performance of cell 5 for parameters other than fecal coliform (N, P,

BOD_5, and suspended solids) was not significantly different than the other cells. This demonstrates how little soil is required to treat many of these substances.

These results reinforce the view that wastewater need be given only minimal pretreatment before land application. No improvement in treatment performance for fecal coliform, BOD_5, suspended solids, N or P was achieved by giving the water conventional secondary treatment before application.

Removal of volatile trace organics

During the last year of the project (1979–80), a study was conducted to determine the removal efficiency for volatile trace organic substances Initially the wastewater was analyzed to determine which volatile organics were detectable, and the constituents consistently found at the highest concentrations (1 to 30 µg/L) were chloroform and toluene. Chloroform and other haloforms were present even without chlorinating the wastewater, presumably due to chlorination of the drinking water supply. The presence of toluene in the wastewater was not explained.

During August and September 1979, the primary wastewater was chlorinated before application to test cells 1 and 6. This significantly increased the chloroform concentration, as expected, but also increased the toluene concentration as well (Jenkins et al. 1980). For these two substances, the concentrations in the applied wastewater over the entire year averaged 41.8 and 57.3 µg/L for chloroform and toluene, respectively.

From October 1979 through May 1980, the wastewater applied to cells 1 and 6 was spiked with a group of volatile organics at the 7 to 60 µg/L level (Table 25). As discussed earlier, significant removal was observed during the spraying process due to volatilization. The concentrations were further reduced to low levels in the test cell percolates (Table 25). For chloroform the levels were reduced to mean values of 0.9 and 0.7 µg/L for test cells 1 and 6, respectively For toluene the removals were even better, with residual concentrations averaging 0.06 and 0.02 µg/L, respectively (Table 25). For these two substances, this removal efficiency should continue since these substances were presumably applied to the test cells for 7 years. For the other substances spiked into the wastewater, the removal efficiency was greater than 98% in all cases. Investigations will have to be continued, however, to determine if these efficient removal charac-

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Table 25. Removal of volatile toxic organics (1979-1980).

	Mean concentration (μg/L)			
Substance	Wastewater before spraying	Wastewater after spraying	Test cell 1 percolates	Test cell 6 percolates
Chloroform	41 8	14 0	0 86 (9)*	0 73 (11)
Toluene	57 3	24 4	0 06 (10)	0 02 (12)
Methylene chloride	7 61	2 32	0 06 (5)	0 04 (6)
1,1 dichloroethane	30 2	9 88	b d (6)†	0 06 (6)
Bromodichloromethane	11 1	3 98	b d (2)†	0 02 (3)
Tetrachloroethylene	61 9	22 7	0 08 (7)	0 35 (7)

* Numbers in parentheses refer to total number of analyses for that substance
† Below a detection limit of about 0 01 μg/L

teristics will continue since these substances were only applied to the cells for several months.

Heavy metal mobility

During the first year and a half of this project, seven heavy metals were injected into the raw wastewater to simulate an industrial component to the waste. This addition was halted in February 1975. Iskandar (1975) presented a discussion of the mobility of these heavy metals following the first several years of wastewater application. In general, the metals were found to be removed quickly in the first several centimeters of soil and did not seem to move deeper into the profile.

In June 1980, we collected additional soil samples with depth from test cells 1 and 6. These samples, along with initial Windsor and Charlton soils, were analyzed for total Zn, Cu, Ni and Cd. The results are presented in Figure 15.

For both cells, these metals have remained near the surface. In no case has significant downward movement occurred. Thus heavy metal movement to groundwater in these soils is very unlikely.
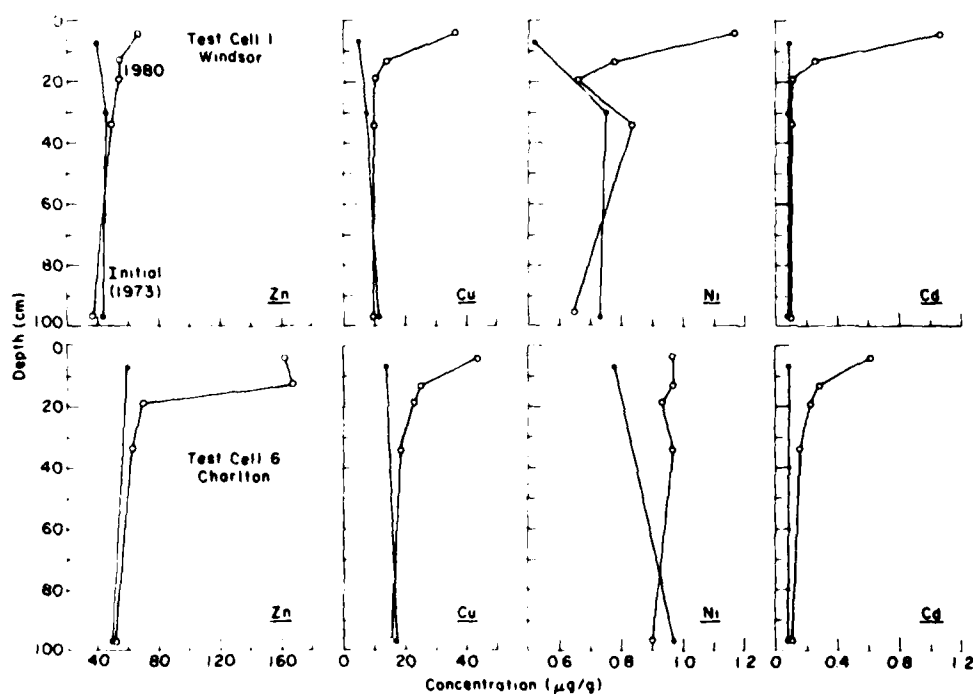

Figure 15. Soil analyses for Zn, Cu, Ni, and Cd.

Table 26. Potassium relationships.

Date	Plant K (%) Cell 1	Plant K (%) Cell 6	Soil exchangeable K (meq/100 g) Cell 1	Soil exchangeable K (meq/100 g) Cell 6	Soil solution at 45 cm (mg/L) Cell 1	Soil solution at 45 cm (mg/L) Cell 6
1973	2.65	2.40	0.12	0.09	6.8	2.0
1974	2.67	2.31	0.14	0.22	1.8	2.8
1975	2.10	2.22	0.06	0.07	1.0	1.1
1976	2.04	1.83	0.07	—	7.4	0.9
Application of 300 kg/ha of K as KCl						
1977	3.39	3.42	0.35	0.44	—	1.5

Potassium/nitrogen balance

While potassium (K) is not of concern as a pollutant, it is an element required in large quantities by plants. Grasses require almost as much K as N. For grasses to take up a maximum of N, sufficient K must be in the soil to fulfill their nutritional requirements.

The wastewater was found to contain 8 to 10 mg/L of K over the 6-year period. This compares with a total N content of between 25 and 30 mg/L. Thus the K/N ratio in the wastewater was between 0.3 and 0.4 compared to an optimum of about 0.9 (Potash Institute of America 1973).

In 1975, following 2 years of applying this wastewater to our test cells, deficiencies in plant K were observed (Table 26). This decline in the percentage of K in the grass continued through 1976. Soil K levels were also found to decline throughout this period, since little K was found in downward percolating waters (Table 26).

To correct this situation, 300 kg/ha of K fertilizer (as KCl) was added to all test cells in May 1977. Plant and soil levels of this element were increased by this addition to more optimum levels.

Following this application of K, crop yields and N uptake improved significantly. While this improvement was coincident with the K addition, the evidence is insufficient to say for certain that the direct cause was the availability of sufficient K in the soil. We do recommend, however, that if the K/N ratio of the wastewater applied to other land treatment systems is well below 0.9, K fertilization be considered. For a more detailed discussion on this topic, the reader is asked to consult Palazzo and Jenkins (1979).

CONCLUSIONS

1. Water balance measurements indicated that plant evapotranspiration and other losses exceeded pan evaporation for all six test cells. The ratio E_t/E_p ranged from 0.86 to 1.17 (Table 13). An average of about 1000 L of water was lost per kg of dry weight of forage grass produced (Table 14).

2. The chemical and bacteriological quality of percolating waters was excellent even when undisinfected primary wastewater was applied. Conventional secondary treatment or disinfection was not necessary prior to land application.

3. An average of 91% of the N applied over a 6-year period could be accounted for in plant uptake and leaching. A majority of the N leached was in the nitrate form. The sum of all other removal mechanisms, including microbial denitrification, accounted for only about 9% of the total N applied (Tables 15 and 16).

4. Overall N removal ranged from 40.4 to 72.5% of the N applied in the wastewater (Table 15). The concentration of nitrate in the percolating water was found to correlate with the N loading rate. To average an application of 10 mg/L of nitrate, a loading rate of about 800 kg/ha was acceptable. For the concentrations of N in our system, this amounted to about 7.5 cm/wk of wastewater.

5. Plant uptake of N was found to be linearly related to the wastewater N loading rate for loading rates below 800 kg/ha. At loading rates above 800 kg/ha, plant uptake of N increased very little, resulting in rapidly increasing levels of percolate nitrate.

6. High concentrations of percolate nitrate are to be expected at times during the first year a new site is irrigated with wastewater. High levels should also be anticipated if the vegetation and surface soils are disturbed for any reason. Lower application rates during these periods should minimize problems.

7. Year-round applications of wastewater did not result in a substantial increase in the concentration of N in percolating waters.

8. Nitrogen treatment was not improved by spreading applications over several days as opposed to applying the same volume in one day. In fact, slightly better treatment performance was achieved with one application period.

9. No significant difference in the effectiveness of treatment was observed for the two soil types tested, a sandy loam and a silt loam soil.

10. Water applied at the surface required roughly 2 to 3 months to percolate to the base of the 152-cm soil profile.

11. Percolate P concentrations were found to average between 0.03 and 0.07 mg/L with only a slight dependence on wastewater loading rates up to 15 cm/wk. Overall P removals were equal to or greater than 99% in all six cells (Table 20).

12. BOD, and suspended solids treatment were excellent at all application rates tested (up to 15 cm/wk). Percolating waters generally had residual levels of these substances below 2 mg/L and a percent removal of > 95% (Table 24).

13. Fecal coliform bacteria were removed to the limit of detectability before water percolated through the 152-cm profile. This removal was independent of whether or not the wastewater was disinfected before application (Table 24).

14. Analysis of trace volatile organics indicated that chloroform and toluene were the most significant components in the chlorinated primary wastewater. Significant reductions in the concentrations of both of these substances occurred during spraying, presumably by volatilization. Further reduction to sub-parts-per-billion concentrations were found in the test cell percolates with overall removals of > 98% (Table 25).

15. Proper crop and soil management will prolong the persistence and extend the life of forage grasses at land treatment sites. Appropriate harvesting procedures, K fertilization, and liming are needed to increase the length of time required prior to site reconditioning.

16. The first harvest period of each year was the most active in terms of total and daily uptake of N.

17. At P loading rates below 75 kg/ha, plant uptake was found to account for over 50% of the P applied. At higher loadings, plant uptake accounted for lesser percentages of the P applied and soil retention of P accounted for the bulk of the P applied.

18. Most of the P accumulation in the soil has occurred in the top 30 cm during 5 years of wastewater application.

19. No significant downward movement of heavy metals was observed 5 years after suspension of heavy metal application.

20. The wastewaters used for irrigation in this study had a K/N ratio of about 0.3. Due to this imbalance and the low levels of K in these soils additional K fertilization was found to be desirable.

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APPENDIX A: EXPERIMENTAL DATA

Table A1. Yearly water balance for cell 1 (June 1974 - May 1980).

Period	wastewater applied (?)	Precipitation (cm)	Precipitation (?)	total applied (?)	Percolate (?)	Difference (?)	sub evaporation (m)	sub evaporation (?)	$P_t \times 1000$ (?)
June 74-May 75	11432?	72.9	59980	170302	108041	61461	66.66	48565	125
June 75-May 76	67047	115.1	88385	155412	98137	57295	69.49	50614	113
June 76-May 77	64861	98.1	75485	140348	89326	51022	54.62	39783	125
June 77-May 78	48283	85.7	65809	114094	84661	42451	52.99	38596	82
June 78-May 79	58417	83.8	64350	122767	73100	49687	51.29	37358	115
June 79-May 80	82778	55.5	42618	125396	88592	36804	50.37	36687	106

Table A2. Yearly water balance for cell 2 (June 1974 - May 1980).

Period	wastewater applied (?)	Precipitation (cm)	Precipitation (?)	total applied (?)	Percolate (?)	Difference (?)	sub evaporation (m)	sub evaporation (?)	$P_t \times 1000$ (?)
June 74-May 75	165680	72.9	59980	401610	328160	73470	66.65	48565	155
June 75-May 76	165395	115.1	88385	253782	184579	69203	69.49	50614	115
June 76-May 77	62911	98.1	75485	148418	100405	48013	54.62	39783	96
June 77-May 78	35481	85.7	65809	101290	77725	23565	52.99	38596	61
June 78-May 79	47366	83.8	64350	111806	68963	42843	51.29	37358	115
June 79-May 80	54890	55.5	42618	97508	71366	25942	50.37	36687	77

Table A3. Yearly water balance for cell 3 (June 1974 - May 1980).

Period	wastewater applied (?)	Precipitation (cm)	Precipitation (?)	total applied (?)	Percolate (?)	Difference (?)	sub evaporation (m)	sub evaporation (?)	$P_t \times 1000$ (?)
June 74-May 75	170908	72.9	59980	224888	188062	38826	66.65	48565	90
June 75-May 76	70004	115.1	88385	158389	101940	56449	69.49	50614	105
June 76-May 77	60650	98.1	75485	136155	95137	40018	54.62	39783	104
June 77-May 78	36622	85.7	65809	102281	82630	19651	52.99	38596	51
June 78-May 79	58092	83.8	64350	122442	84852	37595	51.29	37358	104
June 79-May 80	62312	55.5	42618	104910	78770	26160	50.37	36687	101

* Based on a surface area of 26,290 m².

** Based on a surface area of 22,836 m².

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Table A5. (heading illegible) (June 1974 – May 1980).

Period	Precipitation (mm)	Precipitation (l)	Wastewater applied (l)	Total applied (l)	Percolate (l)	Difference (l)	Pan evaporation (cm)	Pan evaporation (l)	E_t/E_q (x100)
					141445	47063	66.65	48545	76
					120348	35435	69.49	50614	70
					90057	47279	54.62	39783	119
					72244	40347	52.99	38596	79
					82490	43169	51.29	37358	116
					46188	41490	50.37	36687	113

Table A6. Yearly water balance for well 5 (June 1974 – May 1980).

Period	Precipitation (mm)	Precipitation (l)	Wastewater applied (l)	Total applied (l)	Percolate (l)	Difference (l)	Pan evaporation (cm)	Pan evaporation (l)	E_t/E_q (x100)
June 74–May 75	72.9	53980	161961	216941	165938	51003	66.65	48545	105
June 75–May 76	113.1	88385	48565	136950	117244	39706	69.49	50614	78
June 76–May 77	98.1	73485	76659	150144	96552	53592	54.62	39783	135
June 77–May 78	85.7	65809	35378	101187	69428	31759	52.99	38596	82
June 78–May 79	83.8	64350	47922	112272	65291	46981	51.29	37358	126
June 79–May 80	55.5	42618	58910	101528	59069	42459	50.37	36687	116

Table A6. Yearly water balance for well 6 (June 1974 – May 1980).

Period	Precipitation (mm)	Precipitation (l)	Wastewater applied (l)	Total applied (l)	Percolate (l)	Difference (l)	Pan evaporation (cm)	Pan evaporation (l)	E_t/E_q (x100)
June 74–May 75	72.9	53980	109844	165824	129844	35980	66.65	48545	74
June 75–May 76	115.1	88385	92691	181076	129303	51773	69.49	50614	102
June 76–May 77	98.1	73485	68615	141639	89186	52453	54.62	39783	132
June 77–May 78	85.7	65809	44107	109916	69837	40079	52.99	38596	104
June 78–May 79	83.8	64350	59542	123892	76343	47549	51.29	37358	127
June 79–May 80	55.5	42618	81166	123784	75973	47811	50.37	36687	130

* Based on a surface area of 55,790 m².

Based on a surface area of 72,836 m².

Table A7. Annual N balance, test cell 1.

Date	N (kg/ha)							% Missing
	Applied	Precip.	Total app.	Plant uptake	Perc.	Total found	Missing	
1974-75	769	6	775	455	227	682	93	12.0
1975-76	389	9	398	290	112	402	-4	-1.0
1976-77	451	8	459	244	94	338	121	26.4
1977-78	412	7	419	383	109	492	-73	-17.4
1978-79	619	6	625	387	140	527	98	15.7
1979-80	834	4	838	291	275	566	272	32.5
1974-80	3474	40	3514	2050	957	3007	507	14.4

Table A8. Annual N balance, test cell 2.

Date	N (kg/ha)							% Missing
	Applied	Precip.	Total app.	Plant uptake	Perc.	Total found	Missing	
1974-75	2339	6	2345	697	1386	2083	262	11.2
1975-76	964	9	973	277	738	1015	-42	-4.3
1976-77	508	8	516	169	326	495	21	4.1
1977-78	482	7	489	215	107	322	167	34.2
1974-78	4293	40	4323	1359	2557	3915	408	9.4

Table A9. Annual N balance, test cell 3.

Date	N (kg/ha)							% Missing
	Applied	Precip.	Total app.	Plant uptake	Perc.	Total found	Missing	
1974-75	1218	6	1224	550	425	975	249	20.3
1975-76	451	9	460	195	277	472	-12	-2.6
1976-77	497	8	505	199	288	487	18	3.6
1977-78	311	7	318	205	158	363	-45	-14.2
1974-78	2477	40	2507	1149	1148	2297	210	8.4

Table A10. Annual N balance, test cell 4.

Date	N (kg/ha)							% Missing
	Applied	Precip.	Total app.	Plant uptake	Perc.	Total found	Missing	
1974-75	1161	6	1167	498	523	1021	146	12.5
1975-76	430	9	439	211	272	483	-44	-10.0
1976-77	510	8	518	156	220	376	142	27.4
1977-78	342	7	349	198	207	405	-56	-16.0
1974-78	2443	30	2473	1063	1222	2285	188	7.6

Table A11. Annual N balance, test cell 5.

Date	N (kg/ha)							% Missing
	Applied	Precip.	Total app.	Plant uptake	Perc.	Total found	Missing	
1974-75	1111	6	1117	504	513	1017	100	9.0
1975-76	427	9	436	258	190	448	-12	-2.8
1976-77	614	8	622	194	237	431	191	30.7
1977-78	288	7	295	276	226	502	-207	-70.2
1974-78	2440	30	2470	1232	1166	2398	72	2.9

Table A12. Annual N balance, test cell 6.

Date	N (kg/ha)							% Missing
	Applied	Precip.	Total app.	Plant uptake	Perc.	Total found	Missing	
1974-75	738	6	744	417	306	723	21	2.8
1975-76	518	9	527	327	192	519	8	1.5
1976-77	456	8	464	276	125	401	63	13.6
1977-78	376	7	383	323	114	437	-54	-14.1
1978-79	630	6	636	321	169	490	146	23.0
1979-80	832	4	836	327	206	533	303	36.2
1974-80	3550	40	3590	1991	1112	3103	487	13.6

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